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UNDERSTANDING AND MODELING INFORMATION DOMINANCE IN BATTLE MANAGEMENT: APPLICATIONS OF FUZZY COGNITIVE MAPS

Karl Perusich

PURDUE UNIVERSITY
1700 MISHAWAKA AVE.
SOUTH BEND, IN 46634

Michael D. McNeese

HUMAN EFFECTIVENESS DIRECTORATE
CREW SYSTEM INTERFACE DIVISION
WRIGHT-PATTERSON AFB OH 45433-7022

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Human Effectiveness Directorate
Crew System Interface Division
Wright-Patterson AFB OH 45433-7022

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FOR THE COMMANDER

JOHN F. KENT, COL, USAF, BSC
Deputy Chief, Crew System Interface Division
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* Karl Perusich, PhD
Michael D. McNeese, PhD

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
* Purdue University
1700 Mishawaka Ave.
South Bend IN 46634

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The report takes a unique look at information dominance and how it relates to shared situation awareness and the decision making cycles of the OODA-loop. An explanation of information dominance is developed through a historical example of battle management (the Battle of Britain) to demonstrate the various levels of information inter-connectivity. This example is then extrapolated to look at the constraints and options existent within contemporary information dominance. Fuzzy cognitive mapping, a method for eliciting and modeling human interactions in complex situations (such as information dominance) is introduced and applied to a real world scenario. The role of fuzzy cognitive maps (1) as a means to explicate cause-effect relationships in individual and teamwork settings (2) to model emergent complexity in information dominance situations - is described using the context of the real world scenario. The use of fuzzy cognitive maps is reviewed and evaluated for effectively capturing and abstracting knowledge relevant to shared situation awareness.

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PREFACE

Key to the development of situation awareness in complex battlespace environments is the dynamic management of the generation, distribution and synthesis of information. Such techniques become especially critical when teams with distributed knowledge and distributed decision making responsibilities must cooperate to complete a task. With the speed and volume of modern technology to acquire, synthesize and distribute data, developing a similar assessment of a situation across distributed teams becomes problematic. In addition to the thorough presentation of the present state of the battlespace, the successful development of situation awareness requires the capability to project possible courses of actions and their outcomes so an acceptable or optimal solution can be identified.

In this report, the techniques of constructing and using fuzzy cognitive maps is presented as a way to manage the distribution of information in a complex decision space to afford the development of a common situation awareness. The models constructed can be used as software mediators to dynamically manage the distribution and synthesis of relevant data. Fuzzy cognitive maps are qualitative models of complex solution spaces that compare states of quantities to states of quantities rather than numerical values to numerical values. Thus, fuzzy cognitive maps can seamlessly incorporate a variety of information-physical, political, psychological, etc.- that characterize the environment the model is embedded in without the need for developing a common numerical scale for comparing the different characteristics.

Development of a fuzzy cognitive map requires three steps. First, the nodes (states) must be determined and relationships between them assessed. This produces a web of cause/effect relationships that represents a model (or understanding) of both the problem and the solution spaces. Second, strengths for the cause/effect relationships are assigned. Finally, information is inferred from the map to answer what if? questions. In this report a variety to techniques for completing these steps and constructing a fuzzy cognitive map are presented. To illustrate the process and the potential utility of FCM techniques, a map is constructed and used to determine under what conditions an F-15 should be tasked for an attack on a TEL that has launched a SCUD missile.

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1.1 Information Dominance

Information warfare has received wide play recently in the popular press as a new frontier for battle. (Dunnigan 1996) Given the constantly advancing technological horizon to acquire, communicate, and process data about the environment in which combat will take place, it is natural to assume that an *information space* will be the next domain for conflict. Some have even talked of *information warriors* doing battle with keyboards just as their predecessors did battle with guns. (Libicki 1995)

Information warfare can take many forms[1], but the one most relevant here is *information dominance*. War is about coercing one's adversary into a particular kind of behavior, while at the same time preventing the adversary from doing the same. This coercion can be achieved through traditional military means such as force or maneuver, or by understanding better the conditions of the battlespace and taking appropriate actions quicker. Information is used to determine what the correct *situation or answer* is before the enemy can do the same. With information dominance, data is used as a tool to develop this better understanding of the battlespace to find the appropriate answer or most appropriate action quicker than the adversary can.

Chess can be used as an analogy. *Traditional military means* in chess would be using pieces to take an opponent's pieces. As certain pieces of the adversary become vulnerable they are taken. If one's pieces also become vulnerable, they are moved. With *information dominance*, not only does a player have a thorough understanding of the current conditions of the board, for instance, what pieces are vulnerable, but he understands the strategy of the opponent. This player is then able to project moves into the future and with this knowledge devise counter-strategies to foil the opponent. The fact that one adversary *understands* his opponent's situation better means that he can now dictate the course of

[1] See (Endsley, 1997), page 2 for a detailed listing.

the game to bring it to a conclusion favorable to him. In other words, he can coerce the opponent into behaving the way he wants them to. Part of coercion may be the use of deception to lure the adversary into taking certain positions or commit resources (in chess, pieces) to enact a given move while cooperative forces exploit certain aspects of the situation.

Information dominance, then, has two aspects. (Endsley 1997) First, achieving it requires better or more comprehensive data about the battlespace in which the combat will take place. Using the chess analogy given previously, achieving information dominance requires knowing the location and types of all the pieces on the board, both the player's and the opponent's. Information dominance in a chess match would be difficult if data was only available about those pieces adjacent to one's own pieces.

Second, and probably more important, information dominance requires the ability to develop a comprehensive picture of what's going on. (Endsley 1997) This picture must synthesize spatial and temporal data about force sizes and capabilities with one's goals and the intentions of the adversary. It also requires access to historical data and the ability to project a future state or status for the battlespace. Put succinctly, information dominance requires knowing where you've been, where you are and where you are going, and doing this better and faster than the opponent.

In past conflicts, data about the environment in which the combat took place was either unavailable, late or both. Much of the interest in information as a weapon is a consequence of new technological capabilities to generate in real time nearly complete information about the battlespace. (Brown 1996) This has increased the cognitive workload of the decision makers that must assimilate this data to develop a snapshot of the battlespace from which actions can be derived to achieve current goals. Achieving an information edge over an adversary can be done by acquiring data faster, interpreting it faster, or both. An adversary with information dominance has achieved one or both of these over an opponent.

Achieving information dominance in a battlespace requires three kinds of knowledge: knowledge of the physical status, actions, intentions and disposition of friendly forces, knowledge of the physical status, actions, intentions and disposition of enemy forces, and knowledge of the battlespace. (Endsley 1997) For one side to have information dominance over another it must be able to acquire data, process it, interpret it, and communicate it to its units quicker than the opposing side can.

Many of the applications of technology to the military realm have been to provide missing data about some aspect of the battlespace. Radios were introduced to keep units in contact with a higher echelon commander so that this commander could better understand where his forces were, what they were doing, where they were going and what was the nature of enemy resistance they were encountering. With this information the commander could develop a picture of the battlefield, and take appropriate actions to achieve his objectives. Reconnaissance aircraft were developed to give commanders information about areas behind enemy lines, areas for which available information was sketchy because friendly forces capable of monitoring it were absent.

Technology has progressed to the point that data on just about any aspect of the battlespace desired is available in real time. Whereas previously the problem for military commanders and decision makers was a lack of accurate, current information, creating the *fog of war*, one can argue that the opposite problem is now the case. Too much data is generated. With such a huge volume of data available, it has become very easy for decision makers to focus on irrelevant data, ignore relevant data, or become over saturated with data.

The key to information dominance is to filter data so only that that's relevant to the goals at hand need to be assimilated. Data needs to be abstracted into more useable formats more applicable to the decision process. This requires that data be synthesized with goals, constraints, intentions, and actions of the players involved in the battlespace. Information

dominance is getting the right information to the right actor at the right time in the right format, and doing this better than the adversary. (Endsley 1997)

1.2 OODA-Loop Warfare

Information dominance is about using information to condition the decision process to increase both its speed and its accuracy. To fully understand this concept, it is necessary to examine the process of making a decision and assess how information is used to improve it. A useful construction for understanding a decision process is to view it as a cycle with distinct phases. One such cyclical model of a decision process popular within the military community is the Observe-Orient-Decide-Act (OODA) loop. Decisions are viewed as a sequence of steps, explicit or hidden. Although one can question the cognitive validity of the rigid sequence involved in an OODA-loop, the format does provide a useful template for understanding how a decision maker moves from information about the environment to actions to change it. (Whitaker 1996)

The specific phases in an OODA-loop are:

- *Observe*. In the observe phase, the decision maker acquires data about the environment in which he or she is operating.
- *Orient*. The data is synthesized with the goals for the unit involved to achieve some level of understanding of the situation it is in. Through this picture of the situation a determination is made of the *kinds* of decisions that are needed.
- *Decide*. Courses of actions are assessed and projections made of their consequences. From these possible courses of actions, one is chosen for implementation.
- *Act*. The chosen course of action is communicated to the units and decision makers involved, and it is carried out.

An OODA-loop is viewed as a cycle, because it is an ongoing, repetitive process. Each pass through the loop generates actions that, in turn, change the environment in which the decision is embedded. This changed environment then creates new information, which requires a new evaluation. The cyclical nature of the OODA-loop recognizes the feedback

nature of real decisions. Real decisions are a function of their environment, but this environment is also a function of these same decisions.

Information dominance involves shortening the OODA-loop for friendly forces while lengthening it for an adversary. This can be achieved at three different levels: perception, comprehension, and projection. (Endsley 1997) At the perception level data about the battlespace is acquired through sensors, communications and displays. If one side can acquire this data faster, all else being equal, that side will be able to make its decisions quicker, shortening its decision cycle. Comprehension involves integrating the individual items of data into a more meaningful, descriptive form. By abstracting data into these aggregated forms, a picture of the current state of affairs can be built up. The side that can comprehend the current situation faster can react to it quicker, taking or keeping the initiative.

The final level at which information dominance can be achieved by shortening the decision cycle, which requires comprehension and perception, is projection. Being able to postulate the potential outcomes of various courses of actions allows a decision maker to choose from several options. Rather than having to react to a dynamic situation with a set action, possibly inappropriate, decision makers that can project probable changes that result from their actions can identify an optimal solution. (Endsley 1997)

Time becomes a key element in this decision space. But time, used in this context, is relative and not absolute. Achieving information dominance means achieving dominance in the dimension of time. But dominance in time is measured relative to the adversary. Doing things faster is not absolutely necessary to realize information dominance. It is only necessary to do things faster than the enemy can. Information must be acquired and decisions must be made faster than the enemy can do the same. If it takes the adversary three months to complete its decision cycle, then one's decision cycle must be done in under three months. If it takes the adversary three seconds to complete a cycle, then one's decision cycle must be done in under three seconds.

Technology has been a key contributing factor to the shortening of these relative decision cycles. Each military epoch can be characterized by a time scale for an OODA-loop. The following table illustrates how technology has increased the pace of operations and altered the temporal dimension of the OODA-loop. As can be seen, the scale of time in which military decisions and operations occur has steadily and markedly decreased.

	Revolution	**Civil War**	**WW II**	**Gulf War**	**Tomorrow**
Observe	Telescope	Telegraph	Radio/Wire	Near Real Time	Real Time
Orient	Weeks	Days	Hours	Minutes	Continuous
Decide	Months	Weeks	Days	Hours	Immediate
Act	Season	Month	Week	Day	Hour or Less

Source: (Brown, 1996)

Table 1. Time Scales for Military Epochs

1.3 Situation Awareness

Key to completing the decision cycle is comprehending the situation. (Endsley 1997, Brown 1996) Faster acquisition of data or faster communication of orders to subordinate units is meaningless if it does not condition or is conditioned by an understanding of the current situation. In cases where the situation is not comprehended, the OODA-loop is never closed. One can argue that in such a case the cycle time is infinite. The real hallmark of attaining information dominance is developing a comprehensive picture of the situation faster than the adversary, and then executing actions to strategically or tactically exploit these advantages.

Achieving situation awareness among all units involved in the battlespace is a fundamental requirement of information dominance. All friendly units involved in a combat situation must have the right data and interpret in the same way so that a coordinated, appropriate response is undertaken. If some units are denied critical information or if some units

develop an incorrect understanding of the situation, and consequently their role in a response, any synergy from a coordinated response is lost.

Technology can play a role in developing shared situation awareness in two ways. (Endsley, 1997) In the first, sensors, data processing, and communications technology can provide raw information about the location and status of the units in and conditions of the battlespace. From this data an interpretation of the status of the battlespace can be determined and a response developed. It also provides a means for communicating this picture between units. Through this shared information and shared interpretation a coordinated response is possible. Accurate information, situation assessments, and orders are given to the right person at the right time.

In a second, technology can also develop shared situation awareness by creating a delay between an event and when a response is required. (Perusich ISTAS1997) This delay is the result of the speed with which important data is acquired and communicated to the appropriate decision makers. It gives the decision maker the luxury of time; time to assimilate the data and develop more fully an assessment of the situation. Being able to wait means the decision maker has more time to evaluate responses. It also gives the decision makers an opportunity to acquire more data as the situation unfolds, and develop a more accurate assessment of what's going on. With a more accurate assessment of the situation the response finally chosen is likely to be more appropriate. The decision process, under these conditions, is characterized by composure rather than panic.

During the nineteenth century, cavalry was used for armed reconnaissance to identify the location and movement of enemy units. Any information obtained was communicated to operational commanders at the speed of a horse. If enemy units moved as fast as the cavalry, then the information about the attack would be arriving for the commander at about the same time as the attack. This gave little time for evaluating the situation to formulate a response.

If new technology could be used, for example having forward outposts connected to commanders located in the rear by telegraph, information about the impending attack could be received well in advance of the arrival of the enemy. This would give the commander time to wait and collect more information about their size and composition. The additional time would also give the commander an opportunity to formulate a response and to redeploy forces to implement that response. Being aware of the situation and an appropriate response is meaningless without sufficient time to implement it.

Developing situation awareness, then, becomes a key determinant of how quickly a response can be formulated and, ultimately, how successful this response is. Situation awareness can be characterized at three levels, the higher the level the more cognitive synthesis involved. (Endsley 1997)

1. ***Perception***. This is the most primitive level of situational awareness. Teams and units that have achieved this level of situation awareness have acquired data about the relevant elements within the battlespace. Technology has had its biggest impact in improving level 1 situation awareness by providing more data of better accuracy in shortened times. Much of the battlespace has become accessible in real time through the information technology has provided.
2. ***Comprehension***. Level 2 situation awareness involves understanding how the raw data made available through level 1 situation awareness is relevant to the goals and difficulties the unit finds itself in. To achieve level 2 situational awareness, a decision maker must integrate a variety of data with the goals and constraints they are operating under to develop an assessment of the situation.
3. ***Projection***. By predicting the results of courses of actions the best or most appropriate response can be determined. Projecting these future results requires knowledge of the status of the battlespace, models of the dynamics of how different entities within the battlespace will behave, and a comprehension of the situation. If level 2 situation awareness (comprehension) gives a decision maker insight into *what* needs to be done, level 3 situation awareness (projection) gives a decision maker insight into *how* it can

be done. This highest level of situation awareness gives the decision maker the knowledge and time to decide rather than just react.

Developing situation awareness between teams involved in a coordinated response in a combat situation is problematic, especially when the teams are not co-located. The degree to which situation awareness is achieved is a strong function of how battlespace information is communicated between units and decision makers. Direct communication is one means. Individual units lack common information, but share a common interpretation of the battlespace conditions. This common interpretation of battlespace conditions is generally developed by a central command authority that also develops an appropriate response. The battlespace conditions and response are communicated to the various units involved through a chain of command. An important trend of recent technology has been the increased pace of operations in a battlespace making the command and control structure a key bottleneck in the decision making process.

A second way to communicate information for developing shared situation awareness in a team environment is by shared displays. Relevant information about the battlespace is communicated to all units. From this common data the units themselves develop a common interpretation. In a final method, the units share a common perception of the battlespace by co-location. In this case, the units are responsible for both developing data about the battlespace and interpreting it. These conditions are summarized in the following table.

	Data	**Interpretation**
Direct Communication	Limited	Communicated
Shared Displays	Communicated	Unit Developed
Shared Environment	Unit Developed	Unit Developed

Table 2. Impact of Display Environment on Developing Situation Awareness

1.4 An Historical Example: The Battle of Britain

The Battle of Britain is an example of the use of technology to achieve information dominance that contributed to victory by Great Britain. Radar was used by Great Britain in this aerial duel to acquire data about attacking German formations. This information in turn allowed Britain's Fighter Command time in which to formulate a response, conserving its scare resources of fighter aircraft, fuel and pilots. (Perusich ISTAS1997)

Strategic Situation 1940

To fully understand the Battle of Britain and the role radar played, the strategic situation that England found herself in in 1940 must be understood. Great Britain entered World War II in the midst of an uncompleted rearmament effort to improve the size and technological abilities of its armed forces. (Gibbs 1976) The forces available at the start of World War II, almost across the board, were wholly inadequate for the extensive imperial commitments she had. A series of *assumptions* were used about any future war-who the enemies would be, who the allies would be, and where the fighting would take place, that conveniently fit the material and financial resources that the British Empire could muster. This world view changed drastically with the fall of France in 1940. Great Britain found herself fighting in two theaters, Europe and the Mediterranean, with the likelihood of a third, the Far East, with inadequate resources and no active allies.

The fall of France significantly altered the strategic environment for the home islands of Great Britain. With France as an ally, Germany had two options for taking the war to Great Britain. First, since England was heavily dependent on seaborn commerce for raw materials and other resources, she was vulnerable to attacks on her merchant shipping by submarines and surface raiders. Second, Great Britain's economy and war effort could be disrupted by attacks from bombers on factories, transportation networks, and harbors launched from Germany. As long as their bombers were confined to operating from airfields in Germany alone and, consequently, at the limits of their range and unescorted by fighters, these attacks were considered *manageable* by the air defenses of Great Britain. (Hough 1989)

The entire strategic situation changed dramatically for the worse with northern France in German control. (Hough 1989) First, more of England was brought within range of German bombers and, consequently, within range of attack. The time-honored option for England of moving resources to the west side of the island no longer existed. Second, the proximity of airfields in Northern France made additional models of German aircraft in range of targets within Great Britain. This increased the effective size of the German bomber force that Britain's defenses had to deal with. Third, many bombers would no longer be at the limit of their ranges to attack targets in the heavy industrial concentrations in southeastern England. In these attacks German bombers could increase their payloads making their attacks that much more devastating.

Finally, the fall of France created two other strategic problems for Great Britain that could have severely handicapped its Fighter Command. First, the shortened distances from airfields in France to targets in England reduced the reaction time for British defenses. Second, and more important, many of the targets in Southern England were now close enough that German bombers could fly with a German fighter escort. If victory were only measured by numbers of aircraft versus numbers of aircraft, then the fall of France significantly tilted the balance in favor of Germany in the Battle of Britain.

Tactical Situation 1940

Although Great Britain controlled the seas after the fall of France she faced a possible seaborn invasion. A prerequisite for such an invasion was control of the air by Germany. England engaged in a battle of attrition over her skies to prevent such an eventuality. It was impossible for Great Britain to stop all German bombers from getting through to their targets. Fighter Command had neither the aircraft, pilots, nor technology to accomplish this. Instead, Great Britain's goal was to prevent a *knock-out* blow by Germany. Enough bombers had to be stopped to forestall German air superiority and a possible invasion.

600 first line British fighters faced some 2400 German bombers at the start of the Battle of Britain. (Hough 1989) Of these fighter aircraft, some three quarters were top of the line Hurricanes and Spitfires. Even with this qualitative advantage, the preponderance of shear numbers of aircraft in Germany's favor would seem to have given her a decisive advantage. In addition to a lack of aircraft, Great Britain's Fighter Command suffered from insufficient fuel and too few pilots.

Without radar, the reaction time available to mount a defense was severely restricted by the proximity of German airfields in Northern France. If only visual siting were available, the time in which to respond was short enough that fighters could easily be surprised on the ground or scrambled in insufficient numbers to intercept an attack. Mounting an effective defense under such conditions would have required Great Britain to maintain standing patrols of fighters in significant numbers. But Great Britain entered the Battle of Britain with neither the aircraft, pilots, nor fuel for effective standing patrols.

<u>Chain Home Radar</u>

Great Britain, though, did have one technology that it could use for significant advantage in the aerial battle: radar. Under development for nearly a decade by the start of the war, radar was mature enough at this time, although very primitive by today's standards, that it could be deployed in a series of stations along the coasts of England to provide early warning of an impending bomber attack. (Buderi 1996) This radar network was deployed at about the start of the war, and was composed of two separate, but complimentary systems. The Chain Home Radar network had sets deployed at 21 sites along the coasts. It could provide information about bearing and approximate numbers in an attacking formation some 140-170 miles away, but was ineffective below about 3000 ft.

To provide information about formations flying below 3000 ft., a shorter range Chain Home Low network of stations was deployed. It had a shorter range (50 miles) than the Chain Home radar network but provided coverage below its limits. Both networks were outward looking, so neither provided information about German formations once they

were over the coasts of England. To provide additional information about attacking aircraft once they were out of view of the radar networks, a system of manned observation posts scattered around southeastern England was used. (Hough 1989)

Radar provided key early warning data about an impending German attack that significantly increased the time for Fighter Command to react. This alleviated the need for standing patrols. Hurricane fighters needed about 10 minutes from takeoff to reach the 20,000 ft considered standard from which to intercept attacking aircraft. If the Hurricane were scrambled only when an attacking formation was visually sighted, then the *average* range for detection would be about 8-10 miles. A German Ju-88 could cover this distance in 2-5 minutes, significantly less than the time a Hurricane needed to climb to its necessary altitude. Successfully intercepting the attack would require that the fighters already be aloft, i.e. standing patrols would be necessary. Further, the short reaction time available with visual sighting only gave little opportunity to task fighters from other areas to help. Under these conditions, the number of aircraft needed for standing patrols in sufficient density to make an effective defense was well beyond the available resources of Great Britain. (Buderi 1996)

Radar changed this state of affairs by lengthening the reaction time for Fighter Command from a few minutes to a half hour or more. It would take the same German Ju-88 some 30 minutes to cover the 140-170 miles at which they were first detected by the Chain Home radar network. In some cases the reaction time was increased even further, because the radar network could detect and monitor German formations as they organized over northern France.

Fighter Command

Radar alone did not make up for the resource and aircraft deficiencies that Fighter Command operated under as it entered the Battle of Britain. Radar provided the data necessary to achieve level 1 situation awareness, and it provided the time needed to develop level 2 (comprehension) and level 3 (projection) situation awareness. But time,

although an important ingredient, does not alone develop these higher levels of situation awareness. The organizational structure of Fighter Command itself supported the processing of the data provided by radar and other sources in the best way to achieve these higher levels of understanding of the evolving battlespace.

A centralized command and collection structure was adopted by the RAF's Fighter Command for acquiring and disseminating information from the radar stations, observation posts, and fighter airfields. (Buderi 1996) This structure provided significant organizational and tactical benefits. The centralized command and control structure created the environment in which level 2 and level 3 situation awareness could be developed. All data about an impending attack was sent to a central facility at Bentley Priory. Key to the success of the organization of Fighter Command was the careful filtering of arriving data done here before a response was ordered.

It must be remembered that the radar technology used in this early part of the war was especially crude. Two radar stations could detect the same flight of attacking aircraft, but given the inaccuracies of the technology, two separate formations could be reported at two different locations. If this data was not filtered at Bentley Priory before being passed to individual fighter groups, too many fighters would be sent to intercept. And given the limited resources that Fighter Command had, sending fighters chasing non-existent formations would have severely reduced the overall effectiveness of the British defenses. The data filtering and fusion provided by the centralized command and control at Bentley Priory provided the British defenses with a margin of accuracy that maximized the effectiveness of the available forces in defending Great Britain against the aerial attack by Germany.

The most obvious benefit of the command and control structure of Fighter Command was that it got the right information to the right person at the right time, without significant information overload. Information generated at radar stations and observer posts was communicated to Bentley Priory by phone. RAF officers analyzed all available data to give

their best assessment of the evolving situation. They used objective and subjective judgments to ascertain needed information about attacking formations: position, bearing, height, course and strength. Further, these formations could be *watched* over a period of time to update the data and increase its accuracy. With each update, the understanding of the situation improved. Without the lead time radar provided from when an attack was identified to when it had to be intercepted, this *watching* would have been impossible.

After a flight officer had evaluated the available data about an attacking German formation, it was *plotted* on a large table map of southeastern England. Colored-coded wooden pieces, each representing a German formation, were moved around the map to reflect the latest available information. Also included on the map were pieces to show the status and disposition of British defenses (fighters, AA batteries, and barrage balloons). From this map senior commanders could get a fair representation of the overall situation evolving. Not only could they assess what units were in the best position to intercept which attacking formations, but they could project the likely results from different intercepts, thus simulating and predicting battle situations before they occurred. The goal of Fighter Command was never to stop all of the bombers from getting through. The more realistic goal was to stop enough bombers from getting through to make it increasingly costly to the Germans to continue the attacks and to minimize the damage caused by the attacks. The *plot* used by the commanding officers of Fighter Command gave them a global picture of the dynamic situation. From this meta-view they could prioritize the attack, and use the available fighter resources to maximize their effectiveness while minimizing the risk to them.

Once an attack was evaluated defensive assets were allocated. Operational fighter squadrons were organized into fighter command groups (FCG) deployed geographically. Each fighter command group would have a number of individual squadrons dispersed at a number of different airfields within its region. Each FCG, though, also possessed a centralized command and control center similar to Bentley Priory. The central group command center received information about attacking German formations and interception

assignments from Bentley Priory by telephone.[2] Like Bentley Priory, each fighter command group maintained a situation map of the geographic region that was its responsibility. A FCG officer was linked to each airfield under his command by telephone, and each fighter was linked to the control tower at their airfield by radio. Once given orders from the command authority at Bentley Priory, the FCG commander would scramble the necessary fighters.

A tote board was used in the fighter command group situation room to supplement the data provided by the situation map with information about the weather, barrage balloon heights, and fighter squadron status within the region assigned to the particular FCG. Information on the tote board was color coded, with each color corresponding to a *colored slice* on a large clock in the command center. This color coding was used to indicate the recentness of the data. By comparing the color on the tote board with the color on the clock, an officer could judge the *freshness* of the information and thus its relevance to the developing battle. The situation map, tote board, and color coding scheme gave the officers information about the battlespace in 4 dimensions: the three spatial dimensions and the dimension of time that improved the accuracy of the level 2 and level 3 situation awareness that they developed.

Two groups of officers worked the situation map using additional information provided by the tote board. One group had responsibility for monitoring the movements of German formations. This group developed an operational picture of the attack, and formulated the best deployment of fighter aircraft to intercept it. The second group of officers kept British AA batteries off of British fighters and onto German bombers by monitoring the positions and deployments of the fighters.

Great Britain achieved information dominance in the Battle of Britain through the application of a new technology, radar, and through the use of a superior organizational

[2] It should be noted that rarely did radar information go directly to a fighter command group. Instead it was filtered at Bentley Priory and synthesized with other data before it was distributed to the FCG's. In

structure and a situated group interface for managing its defensive assets. Radar provided the needed data and the early warning of a German attack, making possible a more effective deployment of scarce Fighter Command assets. The unique situated group interface that Fighter Command used for analyzing available information allowed them to recognize a change in the emergent situation that afforded the group the ability to adapt and respond to it. The lead time provided by radar and the *information filtering* possible through the techniques used by Fighter Command made possible the development of accurate situation awareness of the developing battle. Lead time and situation awareness gave Great Britain the qualitative edge it needed to overcome the quantitative deficiency it entered the campaign with. Rarely was an attack completely stopped. Instead, British defenses made any German raid costly to execute, and the results, although not inconsequential, not devastating either. Germany was prevented from achieving the requisite air superiority over southeastern England necessary for an invasion across the Channel. (Buderi 1996)

The qualitative superiorities just described in some sense leveled the playing field and created an environment in which victory in the Battle of Britain could have gone either way. A series of German strategic blunders finally tipped the scales in favor of Great Britain. To name a few, the vulnerable radar installations were under-appreciated by the German High Command, and consequently were rarely targeted. (Hough 1989) Faulty intelligence by the Germans overestimated the effectiveness of their attacks and underestimated the capacity of Fighter Command to recover. Probably the greatest error by the Germans was the switch from attacks on RAF airfields to attacks on London at about the time the raids were beginning to seriously damage Fighter Command's operational capabilities. The change in targeting gave Fighter Command the necessary time to regroup and recover.

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this way each fighter command group received the information relevant to it only.

Information Dominance in the Battle of Britain

England achieved information dominance in the Battle of Britain with radar as the enabling technology. This technology provided the crucial time and data for Fighter Command to achieve level 2 and level 3 situation awareness. By attaining situation awareness at the highest level, RAF commanders were allowed some measure of planning in their responses to an attack giving them the initiative in the aerial battle.

The OODA-loop representation can conveniently be used to understand how Great Britain had an advantage in the decision making process during the Battle for Britain. The technology available to Germany had inherent constraints that limited their abilities to adapt in their offensive operations, so they operated from a static decision making cycle. Once an attack was launched changes in the mission were unlikely or impossible. Inaccuracies in navigation made finding a target difficult making incourse flight changes to deceive Britain's defenses nearly impossible. The only real change that could be made in the mission once the formation was assembled and launched was to abort it if British defenses became too dangerous.

The German decision making cycle was fixed for the duration of the mission. Information given to the bomber crews was generally fixed at the beginning of an attack, and could be updated only after the aircraft had returned and a new attack planned. The limitations of technology prevented the dynamic updating of information and the mission as it progressed constraining the Germans to use a fixed mission plan that could not be altered dynamically.

Fighter Command, on the other hand, benefited from the ability to dynamically alter their response as conditions in the battlespace changed. Radar gave them time and key data about the attack. While monitoring the progress of attacking German bombers, decision makers at Fighter Command could obtain information about the attack and the status of their defenses. The crude but effective displays they used, the situation maps and the tote boards, gave the decision makers the right data in the right format. This allowed them to

develop a fairly good assessment of the developing situation. With this information they formulated responses and projected their outcomes. From these formulations they chose one that met their goals. Radar, the data filtering afforded by the organizational structure of Fighter Command and the comprehension capabilities of their situated displays gave them excellent situation awareness. Thus, Fighter Command could proactively respond to rather than just react to an attack.

In addition to developing situation awareness about the battlespace in which the German attack was occurring, Fighter Command could also dynamically alter their response as the combat progressed. Decision making in tasking British defenses was characterized by feedback and replanning. Tactics and deployments could be changed as conditions changed. If weather or AA batteries thinned one attacking formation or caused it to turn back, the original fighters assigned to intercept these bombers could be reassigned to attack another formation. British resources were dynamically managed (i.e. dynamic battle management and coordination), while those of the Germans used fixed plans of actions. In essence, the British limited and obviated many OODA cycles within the decision loop of the Germans, without the Germans being able to debilitate the British OODA loop. This demonstrates both the offensive and defensive nature of information dominance.

1.5 The Battle of Britain 1997

One can extrapolate a similar military situation to today and ask whether information dominance could be achieved in the same way given a variety of potential changes in technology, context, policy, political environments and so on. The short answer is no. Technological advances have increased the capabilities of both the defenders and the attackers. For the defender the technologies of radar and other data acquisition devices have markedly improved in speed, accuracy, and range. Technology has also improved the means to process, display and distribute the data generated. In many cases, though, technology has developed through a paradigm of *just because its possible* with little consideration for the human/team capabilities required nor has it been designed with full

consideration of the environment in which it will operate. Without these, situation awareness may not be as good as was possible during the Battle of Britain.

To begin with, technical advances have markedly improved the capabilities of bombers. New communication and navigation technologies have increased the ability of such aircraft to locate and attack a target. Additionally, new technologies allow course changes and, if appropriate, target changes during the mission. Unlike the German Luftwaffe, modern bomber formations can dynamically manage a mission to fool defenses through stealth, deception, and retargeting.

The advantages that Fighter Command enjoyed during the Battle of Britain, the time made available by radar, tactical advantages from its organizational structure and the situated displays used, would probably not be present if the aerial war were fought with today's technology. Although radar can still provide an early warning, the pace at which operations would take place would minimize any benefits derived from it. With their greater speed, the bombers and fighters would reach targets or engage each other much sooner than in the battle fought in 1941. Additionally, with the bombers capable of stealth and deception, knowledge of the true targets would not be available till the last moment requiring the response to be ordered at the last moment. Even if surveillance technology afforded a window in which attacks could be watched, new capabilities by the attackers would reduce the quality of the situation awareness that might be developed. To return to the OODA-loop construction, British defenses would no longer have the advantage of closing multiple decision cycles within the German's. It would be a real challenge to close one decision cycle before the enemy did.

One advantage that Fighter Command had in the Battle of Britain, its organizational structure, could in fact be a handicap with new technology. Fighter Command acted as a central clearinghouse for the dissemination of information and responses. Much of the reason for information dominance during the battle was because Fighter Command could impose situation awareness on the units engaged in the response. Today, though, the time

to send the data to a central clearing point, evaluate it, formulate a response, and then task the necessary aircraft would be prohibitive. The shear increased pace of operations in a modern air battle makes such a central command and control structure a bottleneck. Relevant data about the battlespace must be sent to individual units, but in such a way that all units participating develop the correct, and the same situation awareness.

The third tool Fighter Command used to achieve information dominance, the situated displays, could also be an important impediment to achieving situation awareness if updated with today's technology, although not an obvious one. The primitive, by today's standards, technologies used by Fighter Command to display the information during the Battle of Britain was also highly effective. To achieve all three levels of situation awareness (perception, comprehension, and projections) requires the acquisition and assimilation of the relevant data. The situation maps and tote boards used allowed commanders access to the temporal and spatial characteristics of the entire battlespace (in this case a geographic area of Great Britain). These situated displays afforded a global view of the evolving battle and gave enough, but not too much, information. The unfolding battle generated data at a pace that could easily be placed on the situation maps or tote boards evaluated by the observing commanders.

Today's aerial battlespaces provide such a large volume of data at such a high rate that the ability of an observer to assimilate much of it is beyond their cognitive capabilities. The trend, though, in display technologies is give each decision maker within a battlespace more information at a faster rate. This tends to induce noise in the comprehension of these decision makers. Not all of the data is relevant to developing situational awareness of the developing mission, but it is still present in the displays and can become distracting. Also, because of the speed with which modern weapons platforms perform their mission, it is easy for their operators to ignore crucial data especially if it is not relevant to the current goal or task. (Endsley 1997) Thus, display technology has increased in capability, but it has also increased in the volume and complexity of the data it presents leading to *information overload*.

1.6 Information Mediators and Fuzzy Cognitive Maps

Information dominance requires that one side in a conflict be able to close its decision cycle and attain situation awareness before the other side does. Any side that can achieve this can dictate the course and pace of actions in the battlespace. The real challenge in a modern multi-operator battlespace is to provide the most appropriate assistance for the management of data to develop situation awareness. The increased speed of aircraft, data acquisition, communications, and generation of information dictates that decisions will be made just as fast. There will be no window in which to *watch* the unfolding battle and develop situation awareness. Each unit will need to receive data in a proper format that allows it to develop all three levels of situation awareness: perception, comprehension, and projection. In the Battle of Britain of 1941, perception and comprehension were aided and developed by technology, but projection was exclusively developed by the decision makers themselves. In a modern battlespace, technology will need to support the development of this level of situation awareness also.

A group decision support system for managing the distribution of data and projecting the outcomes of possible courses of action will be termed an *information mediator*. Such a tool must be able to determine what data is relevant for a particular unit given its mission and be able to abstract it into more meaningful information. It must also project the results of possible courses of action not only on the basis of the goals and status of the unit itself, but also on the goals and status of other units in the battlespace, and on the intentions and actions of the adversary.

Fuzzy cognitive maps will be proposed as such a tool. A fuzzy cognitive map is a *model* of the cause and effect relationships that define a complex system. A unique characteristic of fuzzy cognitive maps is that it incorporates attributes as qualitative states, rather than as numerical characteristics. A properly constructed map can incorporate such disparate information as the speed of an aircraft, the quality of the data received, the political goals

of the adversary, and the psychological demeanor of a commander. Apples and oranges can be seamlessly compared in a fuzzy cognitive map.

A fuzzy cognitive map is a true model in the sense that it can be used to predict changes in the state of the battlespace given its initial conditions. It can be used to evaluate the outcomes of various courses of actions to choose the response most appropriate to the current conditions. Also, it can be updated as new information becomes available. The remainder of this report will provide the details of constructing and inferring information from a fuzzy cognitive map, and show how it can be used as an important tool in managing information so that situation awareness can be developed and, consequently, impose information dominance.

2. FUZZY COGNITIVE MAPS

2.1 Introduction

A fuzzy cognitive map is a transfermational grammar used to model complex systems with emergent, non-linear qualities. By mapping expert knowledge, policies and strategies with demands inherent in a changing environment, the FCM provides an adaptive structure that affords qualitative reasoning as assessed from the current levels/states of a complex system. Such reasoning provides a significant decision support aid for team decision makers.

A fuzzy cognitive map is model of the cause/effect relationships that define a system. It uses a graphical structure with variable concepts defined as nodes, and cause/effect relationships represented by connections between the defining nodes. The strength of the causal connection is represented by some numerical quantity defined on the interval [-1,1], with fractional values indicating partial causality. (Kosko 1987)

A simple statement like: *Speeding somewhat increases my chances of getting a ticket* can be represented by the following map fragment. In this case there are two variable concepts, *speeding* and *chances of getting a ticket*, for which a relationship has been defined, i.e. speeding is a cause of getting a ticket. The strength of the relationship has been qualified, though, by the linguistic hedge *somewhat.*[1] More details on assessing and using a consistent set of numerical representations for linguistic hedges will be given later in the chapter, but for illustrative purposes, the hedge *somewhat* has been given a constant numerical value of 0.6.

[1] Linguistic hedges are adverbs and adjectives that qualify the notions of causality captured in a statement. Without a hedge it can be assumed that full causality exists.

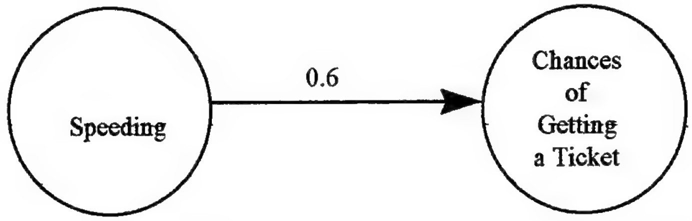

Figure 1. Example of Cause/Effect Relationships in a Fuzzy Cognitive Map

A typical map is composed of a number of nodes with a variety of connections. Also, there is no restriction on the general direction of the causality in the map. Feedback can be present. (Kosko 1986) Often in very complex maps cycles are formed within the structure of the map that tend to intensify or mitigate an effect.

A fuzzy cognitive map can be considered as a type of fuzzy associative memory. (Kosko 1992) A *pattern* of inputs and initial conditions is applied to the map and it is allowed to equilibrate. Individual nodes are updated by adding the causes present weighted by the *strength* of the connection between a cause and an effect. These new node values are then passed through the map, repeating the process. This updating process continues until the map node states reach stable values or a limit cycle.[2] (Kosko 1987) The equilibrium values represent the best *match* between the inputs and initial conditions, and one of the system states stored in the map's structure.

In this chapter the structure of defining and inferring information from a fuzzy cognitive map will be given. The process of eliciting information from a subject matter expert for constructing a fuzzy cognitive map will be given in the next chapter.

2.2 Nodes in a Fuzzy Cognitive Map

Nodes in a fuzzy cognitive map represent variable concepts, and thus the map captures the effects of changes (variations) in the underlying concepts defining the nodes. These nodes are defined to have one of three values: 1, 0, and -1. An important aspect of constructing

[2] A limit cycle is a sequence of node states that repeats.

and of inferring information from a fuzzy cognitive map is understanding the meaning of the state values 1, 0, and -1. Depending on the type of node being dealt with, these state values have different interpretations.

Most, if not all, nodes in a fuzzy cognitive can be characterized as one of three basic types of variable concepts.

1. *Choice Nodes*. These nodes represent the policy or options a decision maker has that impact the resulting state of the system or concept space being modeled by the map. They can also represent or define actions that can be taken. Typically such a node models a statement like: If policy A is chosen then B will increase. The key feature of these nodes is their binary nature.
2. *Status Nodes*. These nodes represent the state or status of some feature of the environment in which the model is embedded, or the status of the system under control. Such nodes are used to represent statements like: If the engine is hot, increase the speed of the fan. A node representing *engine is hot* would be given a value of 1 in this case to capture the fact that the current status of the engine is hot. Like choice nodes, status nodes have a binary character.
3. *Continuously Variable Concepts*. Continuously variable concepts can change over a wide range of values in a continuous fashion. A value of +1 for such a node would mean that the underlying concept it represents has increased, -1 decreased, and 0 no change.

For choice nodes (policy options), the state values represent whether the policy or choice has or has not been made. +1 can be interpreted as choosing the policy represented by a node, with 0 meaning that the choice was not made. If a node is defined as *Deterrence,* then a value of +1 means it has been chosen as a policy. If the node has the value 0, then deterrence has not been chosen. Interpretations of these two nodal values are relatively straight forward.

Setting a policy (choice) node equal to -1, though, is more convoluted in interpretation. In dealing with maps with decision (choice) nodes a policy can be selected and the map

allowed to equilibrate to develop a baseline set of values for the nodes in the model. Given the *state of affairs* that then exists as defined by the model, alternate policies can be selected and applied to the map to see how this state of affairs changes from the baseline case if an alternate policy is chosen. In these cases, the initial policy node is given the value -1 because the policy is being *unchosen*. In keeping with the interpretation of nodes as variable quantities, a value of -1 represents a *decrease* in the choice represented by the node. Thus, -1 is generally used for a choice node value only after the node has had a value of 1, and the map has been processed accordingly.

So, for the example given above, +1 for the node *Deterrence* would mean deterrence has been chosen as the policy, 0 for the node would mean it is not chosen, and -1 would mean that deterrence is *unchosen* as the policy. As can be seen, a policy can not be unchosen until it is chosen, so thus the caveat given above about policy nodes of -1 typically only being used if the node had a previous value of +1.

Status nodes represent the condition of attributes of a system. Like choice nodes, these nodes represent underlying concepts that are binary in nature. A nodal value of 1 means that the condition modeled by the node is present. A nodal value of 0 means it is absent. Unlike choice nodes, though, there is no plausible or meaningful interpretation of a nodal value of -1, so such a situation should be avoided.

The interpretation of state values for general variable nodes is straightforward. A variable node with a value of +1 means that the concept represented by the node increases. If the node has a value of -1, the underlying concept decreases, while a value of 0 means no change has occurred in the concept represented by the node. If the concept represented by a node is *Aircraft Speed*, then a value of +1 for the node means the aircraft speed increases, -1 means it decreases, and 0 means no change in speed.

It must be emphasized that nodes in a fuzzy cognitive map must represent a variable concept. For example, a node might be defined as *Battleship*, with +1 indicating

battleships are present, 0 indicating they are not present, and -1 devoid of an interpretation, but *battleship* is not a variable concept. One can ask whether *increase battleship* or d*ecrease battleship* makes any sense. It does not. Further, *battleship* in no way defines a policy or choice, so it should be properly excluded from a well developed fuzzy cognitive map. If such a node is suggested, its context should be carefully reviewed to determine what about it can change, and how such changes affect other attributes and concepts defined in the map.

A simple alteration for this example could be to change the node definition to *number of battleships* as the defining factor and not *battleship* per se. In this case, +1 for *number of battleships* would represent an increase in the number of battleships, -1 would represent a decrease in their numbers, and 0 would mean no change in the number of battleships.

Sometimes fuzzy hedge-like linguistic interpretations will be given to the node values of 1,0, and -1. For example, +1 might be interpreted as a *high* value for the concept, 0 a *nominal* value, and -1 a *low* value. Although it is possible to construct a consistent map mixing these two different interpretations of nodal values, if possible, it should be avoided. Keeping the increase/decrease interpretation throughout makes understanding the results of a map easier, and avoids many problems. If a nodal concept needs to be differentiated into fuzzy partitions (*high, low, a lot, a little*), then using extended fuzzy cognitive maps, described below, is a better way.

2.3 Edge Strength Values

The strength of a causal connection is represented in a map by the value or function assigned to the edge connecting two nodes.[3] In addition to a numerical value representing the causal strength, the edge is also given a sign. A positive edge indicates direct causality; an increase in A causes an increase in B. Negative edge values indicate inverse causality; an increase in A causes a decrease in B. Because fuzzy cognitive maps can accommodate

[3] An edge in a fuzzy cognitive map is a directed line segment from a causal node to an effect node.

partial causality, the values of the edge strengths are restricted only to the interval [-1,1] and not to the discrete values -1, 0, and 1.

To preserve the basic structure of a fuzzy cognitive map, it will be assumed that the node states are restricted to discrete values of -1, 0, and 1. In this way the map will process states of concepts against states of concepts. The methods used to assign a value (or function) to the edge strengths are many, allowing a variety of different types of data and information to be incorporated into the map. In the remainder of this section, several different methods for mathematically representing edge strength values will be given.

Numerical Values

The simplest and most straightforward method for representing edge strengths is as fractional numerical values on the interval [-1,1]. This value can be assigned or a scale used to map a ranking of linguistic hedges to the interval. In the previous figure the edge strength is given the value of 0.6.

In another situation, three hedges might be used in describing the relationships that define the map and are ranked according to:

1. Very much
2. Somewhat
3. A little

If one assumed a simple linear relationship between the preferences captured by the hedges, then the interval [0,1] could be divided into equal increments and the numerical values assigned accordingly. For this case, *Very much* could be given the value 1, *Somewhat* the value 0.67 and *A little* the value 0.3. This method of assessing edge strength values has the virtue of simplicity and, for most purposes, is entirely adequate.

Hybrid Numbers

It is possible that in some situations a single numerical value fails to capture the nature of the edge strength being represented. This value might best be characterized by a fuzzy

number (for example, *about 0.5*) or by a probability distribution. The most general form that can be used is a hybrid number that has both a fuzzy component and a stochastic component. Hybrid numbers also have the advantage of not artificially combining the fuzzy parts and the stochastic parts[4], thus preserving information. Crisp numbers, fuzzy numbers, and probability distributions are all special types of hybrid numbers, so the analysis presented encompasses all three.[5] In appendix A at the end of the report methods are given for inferring information from a fuzzy cognitive map with hybrid number edge strengths.

Incorporating Numerical Information in an Edge Strength Value

A fuzzy cognitive map is constructed by eliciting the subjective casual reasoning a subject matter expert has about a particular problem space. As such it is a subjective estimate of the dynamics of the problem being examined. As has been stated previously, experts can normally readily identify relevant concepts that effect the problem in some way, and usually can identify linkages relatively easily. On the other hand, assessing the strengths, even if only qualitatively, can be a cumbersome process. In some instances, linkages within a map actually represent subjective relationships between attributes. In other instances, the linkage represents a physically quantifiable parameter. In these cases, the physical parameter is being subjectively mapped to the fuzzy interval [-1,1].

A fuzzy cognitive map is intended to be a true model of the processes and dynamics that represent a problem space. The chief advantage of this modeling approach is that quantities being compared do not need to be measured in the same way, nor does a common metric need to be created to make the comparisons. Each attribute is represented as a causal state. Causal states are compared to causal states rather than values compared to values.

[4] In many applications where both fuzzy and stochastic information is present, either the fuzzy data is converted to probability data before the processing is continued, or the stochastic data is converted to fuzzy data before the processing continues.

[5] A crisp number, such as the values defined in the previous section, are fuzzy numbers with a membership value of 1 at the crisp number and a membership value of 0 for all other numbers not equal to the crisp number.

When available, numerical measures for the interactions between causal nodes can be used to assess the edge strength values of the linkages between them. Maximum and minimum values can be determined for the numerical scales represented by the linkages between the nodes. This interval can then be transformed to the fuzzy interval ([-1,1]) and used in the map. If a relationship can be assessed for the linkage between two nodes that produces a numerical value, this value can be scaled using the measurable range of the parameter. Using such numerical information can enhance the validity of a fuzzy cognitive map.

One approach is to map a bounded range of values for the physical process being modeled to the interval [-1,1]. In essence the values are being scaled to fit the interval [-1,1]. These scaled values are then used as the edge strengths in the map. In this way those relationships that have a higher value in the physical process will give a stronger causal relationship in the map.

As an example consider the following map fragment where a single effect, the round trip travel time, is caused by three possible travel paths, A, B, and C. Assume that the round trip distances, given in the next table, for each travel path are known and that the velocity for each is the same and is constant. To determine the edge strength the round trip distances are scaled, with some value chosen as 1 and some value chosen as 0. The actual limits used for scaling the values are contextual. In this case, assume that 100 is used as the value for 1 and 0 as the value for 0. The edge strengths are then determined as a percentage of the maximum scale value of 100. These values are listed in the table.

	Round Trip Distance	*Edge Strength Value*
Path A	100	1.0
Path B	40	0.4
Path C	20	0.2

Table 3. Assessing Edge Strength Values for Various Trip Distances

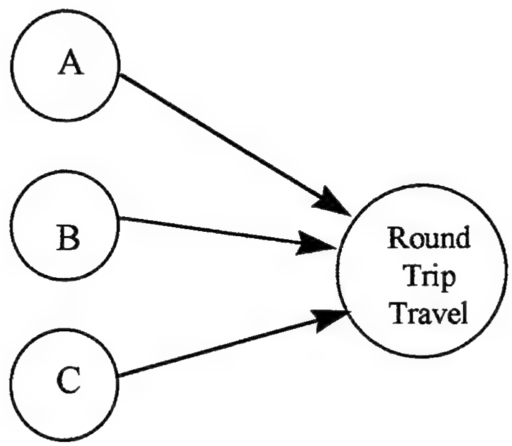

Figure 2. Fuzzy Cognitive Map for Round Trip Travel Time

Variable Edge Strength Values

It is possible that a relationship may exist between two nodes, but its strength may change as the environment changes. In these cases the edge strength for the causal relation can be updated dynamically as the underlying parameter it represents changes. Such variable edge strength values most often occur when the relationship being represented models a physical system. In the previous example, the starting points for paths A, B and C could be such that they change at different points in time. As long as the causal relationships do not change, then the edge strengths can be updated as each new starting point for path A, B and C occurs.

2.4 Inference in a Fuzzy Cognitive Map

A fuzzy cognitive map is similar to a fuzzy associative memory in the sense that initial conditions are applied and the map is allowed to equilibrate. The equilibrium values represent the output of the map. They are the values expected from the initial conditions given the relationships embodied in the map. Equilibrium values in a map are of two types: stable values and limit cycles. Stable values are nodal states that do not change while limit cycles sequences of states that repeat in a particular order.

Initial Conditions

When inferring information from a fuzzy cognitive map, two kinds of initial values are used. All of the nodes must be assigned an initial value, either 1, 0, or -1. These initial values, termed simply the initial nodal states, can change as causes propagate through the map. Once initially set at the start of the inference process, these nodal values change only in response to the nodes that effect them.

A second kind of initial condition used in the inference process is *continuing conditions*. These are nodal values that are held constant throughout the inference process. They are given an initial value at the start, and retain their values even if the casual nodes affecting them infer a change. Continuing conditions are analogous to voltage and current sources in an electrical network. Typically, continuing conditions are the policy choices and environmental attributes that affect the final state of the system under scrutiny. In such cases, one is asking what happens to the system embodied in the fuzzy cognitive map given the continuing conditions with the initial conditions.

Inferring Information

After the initial and continuing conditions are set, they are propagated through the map. Each node is thresholded[6], and any node corresponding to a continuing condition is reset accordingly. Initial conditions are not reset. The process is repeated until one of two conditions results; the map reaches a stable state where nodal values do not change, or a limit cycle is reached. A limit cycle is a sequence of state values that repeats with a definite period, and represent instabilities in the structure of the map given the initial and continuing conditions. Under most circumstances the map will reach a stable configuration of nodal values after a small number of propagations. (Kosko 1987)

In its most basic way, the fuzzy cognitive map can be used to answer *what if* questions. The map is used to deduce what affect can be expected from some set of initial conditions,

[6] Thresholding is the mathematical operation of mapping inferred values to the state values of -1, 0 and 1.

or change in initial conditions. The inferred output is not numerical values for the various attributes defined in the map, but qualitative states for them. Using the example given above, a fuzzy cognitive map incorporating *Aircraft Speed* as a node can not determine the velocity of the aircraft in miles per hour. Instead, the map will infer whether a given set of conditions causes the aircraft speed to increase, decrease, or not change. If more *quantitative* information is needed then the node *Aircraft Speed* can be replaced with several nodes that linguistically partition the measurement, for example, *high speed*, *medium speed*, and *low speed*.

Additive Causality

Updating the value of an effect node is done in two steps. First, the causes are weighted by their edge strengths and then summed to give a value for the effect node. This value is then thresholded, i.e. mapped to one of the state values of -1, 0, and 1. The summation operation for combining the causes to yield the effect can be any valid mathematical operator, but the one that seems to most closely resemble intuitive notions of causality is the arithmetic addition operator. Such an approach can be termed *additive causality*. The idea is that while none of the causes by itself yields the effect, sufficient accumulation of the causes will.

Mathematically the process of updating an effect node can be written:

$$X_i = \mathbf{T}[\ \Sigma_j X_j * e_{ij}]$$

where X_i is the effect node i

Σ_j is an appropriate summation operator

X_j is the cause node j

e_{ij} is the edge strength from node j to node i

T[] is a threshold operator that maps values to -1, 0 and 1

In most cases the summation operator used is addition, and the threshold operator is an order relation such as:

If $X_i>0.5$ $\quad X_i=1$

If $X_i<-0.5$ $\quad X_i=-1$

If $-0.5<X_i<0.5$ $\quad X_i=0$

Techniques for updating node states when edge strength values are hybrid numbers are given in Appendix A.

2.5 Comparing Alternate Decisions: Preference Tables

Very often a fuzzy cognitive map incorporates several policy options and a number of attributes, and the goal is to use the map to judge which of the options is *best* under the given conditions. In such a map there must be some node or nodes that represents a goal, i.e. some attribute that is to be minimized or maximized as a result of the policy choices. Such a node (or nodes) can represent a time factor, a measure of utility, or a profit or loss, to name a few. In addition to the *goal* node there may be other attribute nodes that give further conditions to be met should the policy option under consideration be chosen.

Although each policy option can be used as an initial condition with the map, the results are typically indeterminate. Very often all of the options give a positive result. Each results in an acceptable value for the *goal* node. This occurs most frequently when the goal node has not been differentiated into fuzzy levels (*high, low, medium*, etc.) as in an extended fuzzy cognitive map. In such situations, each policy option can be compared against other policy options to produce a preference table. (Perusich 1997)

In a preference table, the results of the comparisons are tabulated. One policy option is selected for analysis. The initial conditions represented by this policy option are applied to the map and it is allowed to equilibrate. The resulting nodal values represent the *baseline values* used for the analysis. A second policy option is chosen. Its initial conditions are applied to the map, with other nodes retaining the values generated from applying the first policy option. Where necessary, policy nodes representing the first scenario are *unchosen*

(set equal to -1). Any changes in the nodes representing goals are noted. This process is repeated for each of the remaining policy choices being examined.

Changes in the nodes representing goals as scenarios are changed will produce preferences of some choices over others. Ideally, one policy will be preferred over all the others. Practically, the process will narrow the field of acceptable choices. Additional information can also be determined from any attribute nodes incorporated in the map that are affected by the policy choices rather effecting the outcomes.

To illustrate the development and use of a preference table, use will be made of the following fuzzy cognitive map. In this map nodes A, B, and C are considered policy options (i.e. inputs) and node F is considered the output that is being maximized. The policy from A, B and C that maximizes the value of F is the one that should be selected.

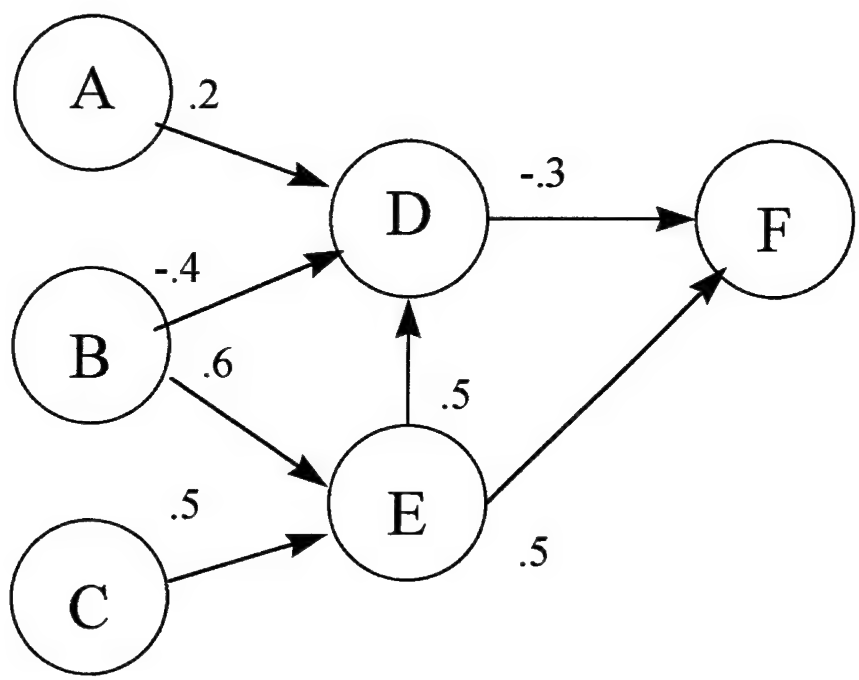

Figure 3. Fuzzy Cognitive Map for Illustrating a Preference Table

To generate the preference table, node A is applied first to the map by setting its value equal to 1 while holding the other policy nodes (B and C) at 0. The map is allowed to

equilibrate giving the initial nodal values for evaluating policy A. The map is reset to these initial values each time the policy option is changed from A to one of the other ones (B or C) by setting A equal to -1 and one of the other policy nodes equal to 1. The value of F is observed each time and the results for node A become the first column in the preference table. Repeating the process for nodes B and C generates the following policy table.

	A	**B**	**C**
A	0	-1	-1
B	1	1	0
C	1	0	0

Table 4. Preference Table for 3 Options in Fuzzy Cognitive Map in Figure 3

Entries in the table represent the inferred value for node F. The first column shows the effect of changing from policy A to one of the other policies on the value of node F. As can be seen, changing from A to either B or C results in better outcome, so option B or option C is preferred to choosing option A. Examining the second column, choosing option B results in a better outcome than choosing either A or C, so B is preferred to either. For column three, choosing B over C produces no change, so choosing option B is indifferent to choosing option C. But option C definitely produces a better result over choosing A, so it is C is preferred to A. Combining all the preferences, option B would be preferred over either A or C.

2.6 Extended Fuzzy Cognitive Maps

In some situations the physical attribute represented by a node can be differentiated into different fuzzy levels each of which causes different behaviors. (Kosko 1997) Such situations are modeled in the map by having each fuzzy differentiation given its own node and different edge connections if the behavior so warrants. These extended fuzzy cognitive maps provide a technique for modeling a variety of different, complex behaviors.

Using the example given at the beginning of this chapter, assume that the consequences are different as the speed changes. Just *speeding* nets the transgressor a warning. *Going fast* will get the driver a ticket, while *going very fast* over the speed limit will get the offender arrested. In each case the underlying cause is the speed of the vehicle, but the exact behavior predicted (i.e. the effect) depends on a fuzzy qualification of this speed. In this case, the vehicle speed would be represented in the map by three nodes, not one. Each node, *speeding, going fast,* and *going very fast* would have different connections to other nodes because each has a different consequence.

The exact node for the vehicle speed activated for the inference would depend on the actual speed. In some cases all three nodes are activated during an inference process with variable edge strength values used, each value a function of the actual speed. As the speed increases the strength of the connections from going very fast increase while the strength of the connections from speeding decrease.

3. CONSTRUCTING A FUZZY COGNITIVE MAP

3.1 General Procedure

In this chapter a variety of techniques will be presented for constructing a fuzzy cognitive map. Although the details vary with the method used, the following general steps can be used as a guide.

1. *Determine the nodes.* An assessment is made of the basic features and attributes to be captured in the map.

2. *Assign edges.* After nodes have been determined, their relationships are examined and edges (connections) are assigned accordingly.

3. *Assess Edge Strengths.* One of a number of methods is used to assign a value or function for the strength of each cause/effect relation.

4. *Extend Nodes.* Nodes are examined and, if necessary, are differentiated into fuzzy levels with connections and edge strength values adjusted accordingly.

5. *Test Map.* Sets of known states are applied to the map and results inferred. If these inferred values are different from those expected, then the map is adjusted.

A part of this process, frequently overlooked, is applying a set of known inputs and outputs, i.e. training data, to the map to evaluate its accuracy. It is through this iterative evaluation that the map can be fine tuned to produce an accurate representation of the system being modeled.

3.2 Determining the Nodes

To construct a map, an evaluation is made of the attributes, policies and choices that are available and are an integral part of the system being studied. Often it is easier to elicit these attributes independent of the relationships that exist amongst them. A hierarchical

approach can be used. First, a determination is made of very broad categories of concepts that may or may not have an impact on the system. Each category can then be refined by evaluating different attributes, concepts, conditions, constraints, or variables that may impact the category. In certain cases, key concepts will be found common to several broad categories indicating cross relationships. These individual concepts can then be further refined to reach some level of differentiation which the subject matter expert believes represents closure. As cause/effect relationships are identified additional concepts or further refinements of nodes may be made.

As an example, consider the process of identifying nodes for the tasking of a U-2 surveillance aircraft for a SCUD-hunting mission.[1] The attributes to be examined for determining whether to task a U-2 for a TEL[2] surveillance mission can be broadly classified into three categories: attributes that impact the U-2, characteristics of the TEL launch area, and attributes that impact locating and monitoring the TEL. The final decision to be made is whether or not to task the U-2 from a mission in progress to locating and monitoring the TEL.

Additional information about each of these can be elicited by identifying different concepts associated with it. In some cases these additional concepts are the status of a system or characteristics of the battlespace environment. In other cases they are questions about decisions or characteristics that need to exist or will impact the final decision. These additional concepts are identified in the following table.

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[1] The results outlined in this example were part of a knowledge elicitation session with a student-volunteer. The project involved eliciting information from several volunteers about the tasking of air assets in a hypothetical Korean war that involved SCUD attacks on South Korea. This particular student volunteer had the assignment of developing rules of engagement for tasking U-2 surveillance assets. This scenario is used for study purposes only and is not meant to be a representation of actual mission or scenario.

[2] The TEL (Transporter-Erector-Launcher) is the vehicle that moves and launches a SCUD ballistic missile. Normally it is the target of an attack rather than the missile.

U-2	Are enemy defenses present in route to patrol area?
	Can enemy detect U-2?
	Will U-2 be shot down before it finds TEL?
	How long can the U-2 patrol?
	Fuel capacity of U-2
	Fuel consumption of U-2
	Other mission U-2 is on
TEL Launch Area	Characteristics of TEL
	Speed at which TEL can flee
	Defenses of or near TEL
	Number of TEL's in area
Locating and Monitoring TEL	Terrain

Table 5. Subcategories for Knowledge Elicitation for Tasking a U-2 in a SCUD-Hunting Mission

Each of these individual concepts can be further refined. One effective way is to pose questions about the concept as it relates to the mission goal or some other significant attribute. In this example the decision concerns tasking the U-2 to monitor a TEL. For example the terrain can be differentiated into three types: flat, jungle, and impossible types.[3] Each can then be further differentiated by a chain of reasoning about how it would effect the decision to task the U-2. In this example the subject matter expert reasoned that flat terrain would make it easy to detect the TEL so the U-2 should be tasked. Also, jungle would make it hard to detect the TEL, but not impossible, so it may or may not be desirable to task the U-2. And finally, impossible terrain would make it unlikely to detect the TEL so the U-2 should not be tasked. As can be seen in each statement additional concepts are identified as are causal relationships which are necessary in the next step of

the construction process. Although information about cause/effect relationships is elicited in answers to these questions, the process works best if a top down, incremental approach is used.

3.3 Assigning Edges

Edges are directional connections between nodes in a fuzzy cognitive map. They signify a causal relationship between the underlying concepts identified with the nodes. Edges are always directional because causality is directional. A *causes* B. Eliciting edges is best done without reference to the strength of the relationship. Constructing a fuzzy cognitive map can be a confusing process, so organization/management of the process is desirable. (Kosko 1987)

The most effective way to identify linkages between nodes is to elicit *chains of thoughts*. (Juliano 1996) Subject matter experts are asked to reason through a chain of causality from a concept to another important concept or an output node. Such reasoning would take the form of asking how an increase (or decrease) would ultimately affect the output.[4] Each chain will typically step through a number of nodes before the final output is reached. Overlap will exist between chains, which is desirable. Such overlap adds further confirmation of the linkages of the particular nodes. Although the process can be a bit haphazard in that it doesn't provide a systematic coverage of all the nodes, it does provide a true representation of the mental model of the subject matter expert.

An alternate method is to simply pick a node and ask the expert to identify all the other nodes that cause it. Although this method has the advantage that the nodes are covered in a systematic fashion, it has the disadvantage that it typically introduces noise. Because the expert is forced to focus on a single node, he typically looses sight of more global relationships that can exist. This can induce *phantom* relationships in his thought

[3] These might include urban areas, dense forest, mountains, etc.

[4] It should be remembered that fuzzy cognitive maps capture how changes in causes affect changes in effects.

processes. He thinks that a node should affect another node, but it in fact does so only through some complicated *chain* of cause/effect relationships.

Using the U-2 tasking information provided above, a chain of reasoning might proceed something like the following. If defenses are present in the TEL area then the chances the U-2 will be shot down increase. If the chances the U-2 will be shot down increase, then the chances it can monitor the TEL decrease. Decreasing the chances the U-2 can monitor the TEL decreases tasking the U-2. As can be seen with this example several nodes are involved in relating enemy defenses in the TEL area to tasking the U-2.

3.4 Assessing Edge Strengths

Of the steps involved in constructing a fuzzy cognitive map, probably the most difficult is assessing edge strength values. The edge strengths are assessed a value or function on the interval [-1,1]. (Kosko 1987) Values -1 and 1 indicate complete causality. An increase in A causes an increase in B. Fractional values represent partial causality. Such fractional values equate to linguistic qualifiers of the relationships defined by the underlying concepts encapsulated in the nodes. An increase in A *somewhat* causes an increase B, or a decrease in A *significantly* increases B.

The process of assessing edge strength values is done most effectively when it is broken into two, independent steps. In the first step, each edge is examined to determine if it represents a direct or an inverse relationship. In a direct relationship an increase in the cause results in an increase in the effect, and likewise a decrease in the cause results in a decrease of the effect. If an inverse relationship exists the opposite holds. Decreasing the cause increases the effect and increasing the cause decreases the effect. In the second step, some method is used to assign a strength to an edge to represent the strength of the relationship being modeled.

Several methods for assessing edge strengths will be presented in this section with the strengths and weakness of each detailed. Any map with a relatively large number of nodes

will necessarily require a large number of assessments to be made. Care must be taken when working with a subject matter expert to assure that the assessment process does not become lengthy or it will suffer from cognitive inconsistencies. In fact, it is often better in large maps to use several experts with each having responsibility for assessing a subset of the edge connections.

Direct Assessment

In this method, a subject matter expert is asked to simply examine the cause/effect relationship represented by a connection and give an assessment of the strength of the relationship. This assessment can be a numerical value[5] or a linguistic modifier chosen from a predetermined list that describes the relationships. The listed values can then be assigned numerical values on the interval [0,1] based on a cardinal rank ordering of these linguistic modifiers.

Sometimes these linguistic strengths will occur naturally in the description as the subject matter expert provides a chain of reasoning for the cause/effect relationships in the map. Although this method would seem to provide the best framework in which to assess edge strengths because the expert concentrates on only one relationship at a time, its major drawback is also the fact that the expert concentrates on only one relationship at a time. By concentrating on only one relationship at a time, there is no mechanism for assuring that relationships that have similar strengths in different parts of the map will be given the same modifier or numerical value. In large maps, the differentiations provided by experts tend to narrow as more edges are examined.

Forward/Backward Chaining

In this method, a subject matter expert traverses the map in a prescribed manner, giving relative comparisons of edge strength values at each node. The expert starts with a node[6] and examines all of the causes (connections emanating from it) affecting it. The expert is

[5] The expert might be asked to select a value from 1-10 with 10 the strongest and 1 the weakest. These values can then be mapped to the interval [0,1] with 10 corresponding to 1 and 1 corresponding to 0.1.

asked to compare these causes against each other to determine which ones have the same strength, which ones are stronger, etc. Typically some arbitrary numerical scale is used. For example, an average node might be given a 5, nodes that are weaker, values less than 5, and nodes that are stronger, values more than 5. If a particular node has six causes emanating from it, and four of them have about the same strength, than these four edges would temporarily be given the value of 5. Lets say that a fifth edge from this same node is considered very much stronger, then it could be given a value of 8 to reflect this. The sixth edge might be slightly weaker than the average nodes, so it might be given a value of 4.[7]

The process then proceeds along one of the edges to another node, and relative comparisons are made of all of the causes emanating *into* the node. The process is again repeated, either with a different edge emanating *from* the first node, or along an edge emanating *into* this node. This process is repeated until all of the nodes are covered through this forward chaining/ backward chaining technique. In many maps several completely distinct edge groupings result.

The underlying premise of this technique is that these relative comparisons are linked through the edges involved in the forward chaining/backward chaining. These linkages can then be used to develop an overall set of strengths. The paths of chaining are retraced in the map. At the first node, the numerical values are preserved or assigned some numerical value. For example, it may be decided that the 5, which in the relative comparison simply meant that the strengths, compared to each other, were the same, might now represent only a weak relationship. This relationship might now be given an *absolute* value of 0.2. The edges at this node are then scaled accordingly. A value of 4 would be given an

[6] The exact node to start with is relatively arbitrary.

[7] When implementing this method in practice, it is more successful if the subject matter expert is presented with a list of linguistic modifiers that are rank ordered and correspond to the numerical values 1-9. 5 would be *about the same*, 4 would be *slightly less*, 6 would be *slightly more*, etc.

absolute value of (4/5)*0.2=0.16. A value of 10 at this node would be given an absolute value of (10/5)*0.2=0.4. This will result in absolute edge strength values for this node.[8]

The absolute value just generated is translated along an edge used in the forward/backward chaining process, and then scaled using the relative comparison values generated at this node in the first step. For example, assume the absolute value along an edge from the first node is 0.2. This value is then translated along an edge to a second node. The absolute value of this edge at the second node remains 0.2. At the second node, assume that it has a relative strength of 6. Any other edge at this node with a relative value of 5 would be given the absolute strength of (5/6)*0.2=0.1667. An edge with a relative value of 8 would be given an absolute value of (8/6)*0.2=0.2667. This process continues from node to node until the map is covered.

The chief disadvantage with this method is the possibility for inconsistency in the evaluations. It is possible, even likely, that if, in the process of forward chaining/backward chaining, a node is arrived at from two different nodes that an inconsistent evaluation of absolute strengths is possible. For example, assume that in the process of assessing edge strengths at a node, two edges are given the same relative values. Next assume that through the chaining process one of these edges is given an absolute edge strength of 0.2 and the other an absolute value of 0.3. An inconsistency has resulted because they should have the same values. It is possible to use these inconsistencies as a diagnostic tool and work with the subject matter expert to remove them through a re-evaluation of the relative and absolute comparisons.

Binary Comparisons

A final method that will be outlined in this chapter utilizes the fact that updating an effect is a result only of the current values of the causing nodes. This means that a node is independent of the updating processes of other nodes. A determination can be made of

[8] It should be noted that because the initial comparisons are relative only, these initial absolute values can not be translated to other nodes. That is 0.2 corresponding to the relative value of 5 does not mean

sets of causing states, and the edge strengths mathematically adjusted to yield the desired result. This method involves establishing a table of binary states for the causing nodes and working through this table in a sequential fashion until all combinations of causing nodes have been determined.[9] These sets of causing states for the nodes can then be used to assess numerical values for the edge strengths that, during an inference process, give the desired (or expected) outcomes for a set of inputs.

This process can best be illustrated by an example. Consider the map fragment in the next figure. Node D is caused by three other nodes, A, B and C.

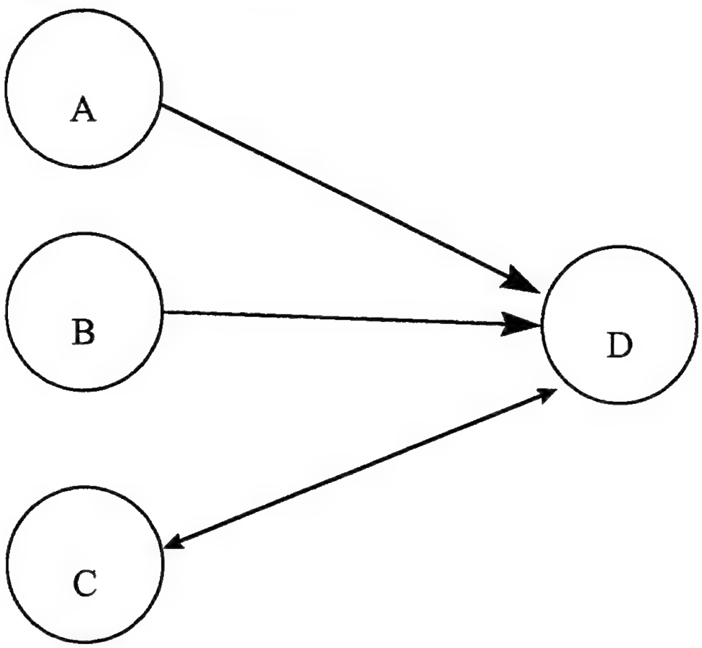

Figure 4. Example Fuzzy Cognitive Map for Assessing Edge Strengths by Binary Comparison

In general, if there are n causing states, then there will be 2^n possible combinations of these causing states (i.e. different combinations of state values of 1 and 0 for the causing nodes).

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necessarily that it will also correspond to the relative values of 5 at other nodes.

[9] The general outline given here requires that the node states be further restricted to values of 0 and 1, with the state -1 prohibited. Any map can be restructured to accommodate this restriction with the use of *dis-states*. See [13]

In this case, there will be 8 (2^3) possible combinations of state values. These values can be conveniently arranged in a tabular format.

Line	A	B	C	D
1	0	0	0	
2	0	0	1	
3	0	1	0	
4	0	1	1	
5	1	0	0	
6	1	0	1	
7	1	1	0	
8	1	1	1	

Table 6. Truth Table for Assessing Edge Strengths by Binary Comparison

Each row in the table corresponds to one particular combination of the causing states. For example, line 6 in the table represents the case where A=1, B=0 and C=1. In theory, the subject matter expert would be asked whether each combination resulted in D being a 0 or 1. In other words, does a particular combination cause the state represented by D?.

In practice, this assessment process can be significantly simplified. If the presence of state A (A=1) alone causes D (D=1), then all other combinations that involve A will also result in D. In this example, if it is determined that A alone causes D, then all rows in the table that include the value of A=1 will also result in D=1 (lines 5, 6, 7, and 8). If B and C together cause D then all rows in the table that involve this combination can be completed with D=1 (lines 4 and 8). Thus, even though there are 2^n possible combinations to evaluate for each node, the actual number that must necessarily be evaluated can be significantly reduced. The goal is to identify those combinations of causing states that result in the effect.

Assume, for example, that for the map fragment given above that D results if either A is 1 or B and C are simultaneously 1. The next step then is to choose edge strength values that will make D a 1 for these combinations. Updating nodes involves summing the causes weighted by their edge strengths, and then thresholding this result to map it to the nodal values of 0 and 1. In most cases the thresholding operation can be adequately accomplished using the following relational operator:

$$\text{if } \sum \text{causes} > 0.5 \qquad \text{then effect} = 1$$

$$\text{if } \sum \text{causes} < 0.5 \qquad \text{then effect} = 0$$

The sum of the causes is the node value of the cause (either 0 or 1) multiplied by the edge strength value. By identifying the combinations, a system of conditions can be established from which numeric values, not necessarily unique, can be determined. For this example, define the edge strength from A to D as e_{AD}, the edge strength from B to D as e_{BD}, and the edge strength from C to D as e_{CD}. Given the thresholding operator defined above, the following conditions must be satisfied by the edge strength values:

$$e_{AD} > 0.5$$

$$e_{BD} + e_{CD} > 0.5 \qquad \text{and} \qquad \begin{array}{l} e_{BD} < 0.5 \\ e_{CD} < 0.5 \end{array}$$

The <0.5 restrictions on e_{BD} and e_{CD} are necessary to prevent either B or C from individually causing D. Actual numerical values in this case are not unique. Possible valid values are:

e_{AD}	0.8	0.7	0.6
e_{BD}	0.4	0.4	0.3
e_{CD}	0.4	0.2	0.3

Notice, as in the middle set of values, there is no restriction that e_{BD} and e_{CD} be equal. Any of these combinations could be used in the map to give the desired results.

This method has the advantage that the subject matter expert must evaluate sets of causes rather than the strengths themselves. Many times it is cognitively easier to identify which combinations of causes must be present to result in the effect, than to attempt to identify a strength for a particular relationship.

Other Methods

As described in the previous chapter it is possible to utilize information generated from a physical or mathematical model of the underlying process represented by a node to generate the edge strength values. This is the preferred method when a functional relationship rather than a numerical value is used as the edge strength. The three methods described previously work best when edge strengths are defined by simple numerical values.

3.5 Extend Nodes

Although placed as a distinct step, extending nodes in a fuzzy cognitive map is really more of a continuous process. As new information provides new insight into the relationships that exist it may be necessary to differentiate a node into several fuzzy levels. (Kosko 1997) Typically, nodes are extended only when a different fuzzy level of the underlying concept represented by the node results in different behaviors.

3.6 Test the Map

Once a map has been constructed, validation is done by applying a set of known inputs that have known (or desired) outputs to the map and comparing the outputs the map infers with the values expected. Differences between the inferred values and the expected values require the edge strengths or the connections to be adjusted to yield the desired results.

This process of testing/adjusting can take several iterations before the map satisfactorily reflects the relationships modeled in it.

4. Tasking an F-15 in a SCUD Hunting Mission

4.1 Introduction

In this chapter the various methods and techniques described previously are used in the construction and analysis of a fuzzy cognitive map for the tasking of an F-15 to attack a SCUD-armed TEL. The map constructed and the analysis provided are meant to illustrate the processes involved so, as such, the assumptions made are meant only to be plausible and not definitive.

4.2 SCUD Hunting

In the Persian Gulf War, the location and successful destruction of transporter/erector/launchers (TEL's) became a prime mission of Allied air assets. (Mandeles 1996) Given their limited range and poor accuracy, a successful SCUD attack had more political than military value. The success of an attack on a TEL depended on the coordination of several units: attack vehicles such as F-15's, surveillance assets such as JSTARS or U-2's, refueling aircraft, if necessary, etc. Providing shared situational awareness between the various units participating was an important indicator of the chances of success of the mission. Additionally, this shared assessment needed to incorporate the threats and actions of the Iraqis trying to counter the attack and prevent the loss of the TEL.

4.3 Tasking an F-15

The F-15 is the chief, but not the only, aircraft in the US inventory capable of attacking a TEL. A fuzzy cognitive map of a SCUD-hunting mission for an F-15 will be constructed to illustrate the tools previously described. In broad mission terms, an attacking F-15 has two overriding goals: to destroy the TEL and to return safely from the mission. These two goals result in four possible outcomes illustrated in the following table.

		TEL	Destroyed
		NO	YES
F-15	NO	Don't	Don't
Survives	YES	Don't	Task

Table 7. Outcomes for Possible Conditions for Tasking an F-15 to Attack a SCUD TEL

In this simple goal analysis, the F-15 should be tasked under only one condition, when it can destroy the TEL and return from the attack. In the other three cases, either the TEL remains unscathed, indicating the mission is a waste of time and assets, or the F-15 fails to return from the mission, which should be considered unacceptable. Thus, the fuzzy cognitive map to be developed will be used to identify battlespace conditions under which the F-15 can destroy the TEL and return from the mission.

4.4 Factors Affecting the Success of an F-15 Attack

A great many factors will affect the success of an F-15 attack against a TEL. To keep the information in the map manageable, only a few key factors will actually be incorporated. Since this map is meant only to illustrate the construction and uses of a fuzzy cognitive map and not to be a definitive model of the battlespace environment in which an attacking F-15 operates, this compromise is acceptable. In general terms an F-15 attack on a TEL follows these steps:

1. *The target is located.*
2. *The F-15 travels to and finds the target.*
3. *The target is attacked.*
4. *The F-15 returns to base.*

Each of these steps will be affected by and affect a variety of factors.

Locating the Target

Locating the target involves a process of finding it. Initial satellite or JSTAR information may provide only general area information about the TEL, or it may provide a very precise location. Without precise location information, the F-15 may have to hunt for the target once it has arrived in the area. Finding the TEL, once the F-15 has arrived in the area, can be confused by the presence of decoys or by a deliberate effort by the TEL to flee and hide. A long hunt will give the TEL time to flee or hide increasing its chances of surviving. A long hunt will also use fuel. If the F-15 has insufficient fuel then the mission could be compromised.

Traveling and Finding the Target

Traveling to the target will be most affected by the range to it and the initial fuel load of the F-15. If the target is close, then the F-15 can travel to it quickly, reducing the chances the TEL will have time to flee or hide. But, traveling fast will cause high fuel consumption that could compromise the mission if the F-15 doesn't have enough initial fuel. Reducing the speed could reduce the fuel consumption, but it would also increase the time to reach the target, which, in turn, would increase the chances that the TEL could flee or hide, reducing the probability that the F-15 locates it.

Attacking the Target

A successful attack by an F-15 on a TEL will be impacted by a variety of factors. First and foremost, the F-15 must arrive at the target and find it. In addition to fuel and range considerations, whether the F-15 reaches the target will also be affected by the presence of enemy air defenses in the flight path. Terrain will be an important consideration. Flat, relatively sparse terrain will favor an F-15. In this situation, the F-15 should be able to identify potential threats and take evasive action. Wooded, hilly terrain would give enemy defenses more opportunity for camouflage and more chances to surprise an attacking F-15.

The weapons load of the F-15 is also critical to the success of the attack on the TEL. If the aircraft does not have the proper mix of ground attack ordinance, then the TEL can not be attacked even if it is located. On the other hand, increasing the air defense ordinance of the F-15 will negate the effectiveness of any enemy air defenses present, increasing the chances of success

for the mission. Thus, the ordinance mix of the attacking F-15 will have a critical impact on whether the TEL can be attacked and destroyed.

Returning to Base

Successfully returning to base will be a function of whether the F-15 survives the attack and whether it has sufficient fuel to return. Although initiating a tactic that involves high fuel consumption may increase the probability that the TEL will be located and destroyed, it will also increase the chances that the F-15 will have insufficient fuel remaining to return to base. Any threat to the survivability of the F-15 will increase the chances the crew will not reach base.

4.5 Constructing the Map

Construction of the map will be divided into four functional parts: localization of the target, range to the target, fuel consumption of the aircraft, and attacking the target and surviving. Submaps will be constructed for each of these functional parts. Once completed, the submaps can be analyzed to assess any cause/effect relationships that may exist between nodes defined in it and other submaps.

Localization of the Target

Localization of the target refers to how well initially the TEL has been pinpointed by a surveillance asset before an F-15 is tasked. Increasing the localization of the target reduces the need to search for the TEL once the F-15 has arrived in the area. Decreasing the need to search reduces the time it takes the F-15 to find the target. Reducing the time to find the F-15 decreases the ability of the TEL to hide, which, in turn, increases the chances the TEL will be destroyed. The presence of decoys will increase the need to search for the TEL and it will also increase the ability of the TEL to hide.

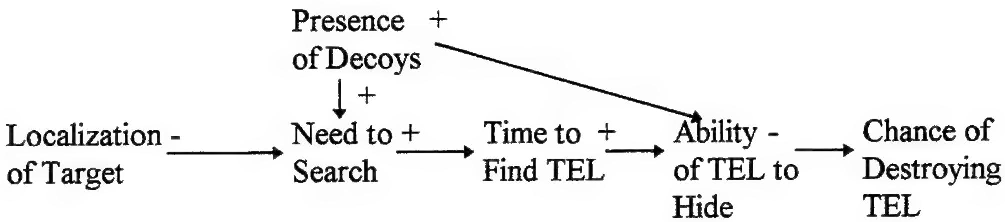


Figure 5. Cause/Effect Relationships for Destroying TEL

Range to the Target

The range to the target will primarily affect how long it takes the attacking F-15 to arrive at a position to attack the TEL or to conduct a search to find it. Reducing the time it takes to reach the target, will reduce the time available for the TEL to flee. Using the technique of an extended fuzzy cognitive map, the range to the target will be divided into two nodes, close range and long range. Each concept presents a different situation that needs different actions. Likewise, the time to reach the target will be represented by two nodes: short time to reach target and long time to reach target. Taking a short time to reach the target will reduce the chances that the TEL can flee, while taking a long time to reach the target will increase the chances that the TEL can escape.

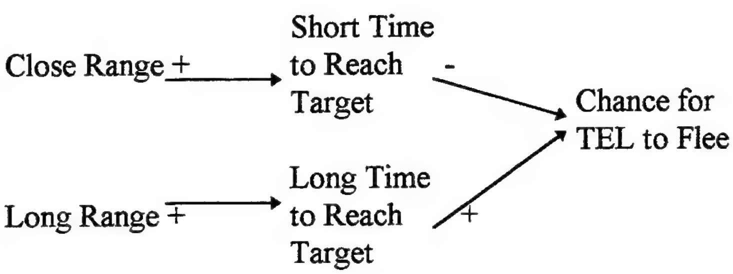


Figure 6. Cause/Effect Relationships on Chances of TEL Fleeing

The time that it takes to reach the target will also effect the ability of the TEL hide. The longer it takes for the F-15 to reach the target the more time the TEL has to hide, the greater the likelihood that the TEL will successfully evade detection. Also if the TEL can successfully flee the area, then the chances of it being located and destroyed are greatly diminished. Thus, there are *cross-linkages* between nodes for the two previous submaps, indicated in the following composite graph by dotted lines.

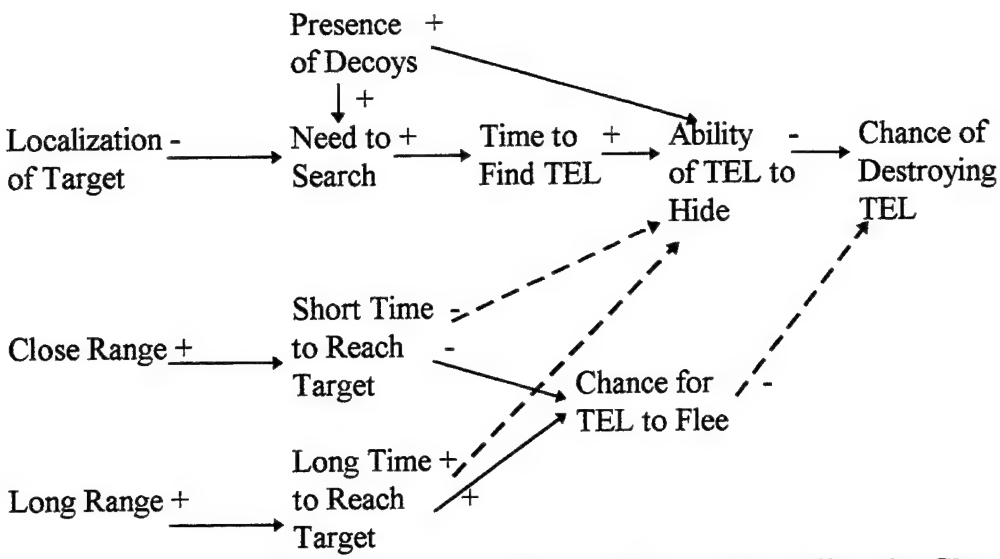


Figure 7. Combined Fuzzy Cognitive Map of Causes that Affect the Chances of Destroying a TEL

Fuel Consumption of the Aircraft

Fuel plays a very important role in the success or failure of this mission. Whether the aircraft can reach the target and return to the base will be a function of how much fuel is used during the mission and how much the aircraft initially starts with. Like the range and times in the previous section, the key factors impacting whether the aircraft will reach the target and whether it will return to base, speed, fuel consumption, initial fuel on the aircraft and fuel remaining, will each be differentiated into high and low states. High speed will incur high fuel consumption that results in little fuel available if the initial fuel was low. Low speed will lead to low fuel consumption. This will result in sufficient fuel available if the initial fuel was high. If sufficient fuel remains or is available for the mission, then there is a strong chance that the F-15 can reach a target and return to base. If little fuel remains, then the likelihood of the plane reaching the target and returning to base is reduced, perhaps significantly.

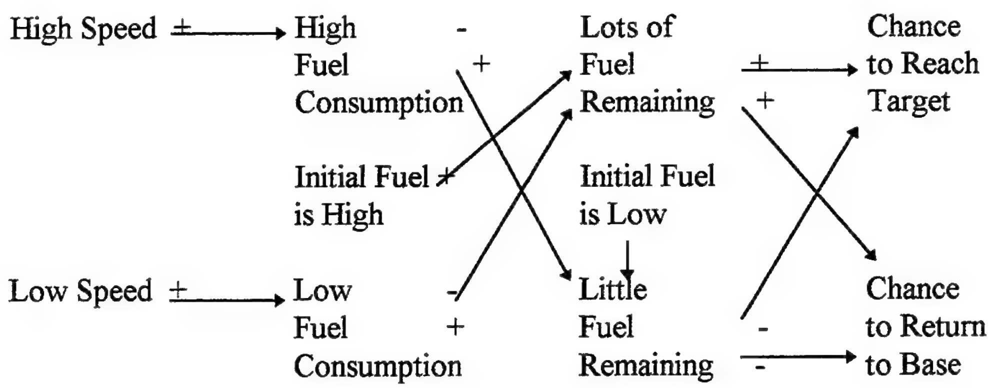


Figure 8. Cause/Effect relationships on Reaching Target and Returning to Base

As with the development of the previous functional parts, factors affecting the fuel consumption of the aircraft will also affect attributes in other functional parts. The speed of the aircraft will affect the time it takes the aircraft to reach the target. Regardless of the speed, whether high or low, taking a long time to reach the target will cause high fuel consumption. Likewise, increasing the time to find the target will increase the likeliness that the fuel consumption is high. Incorporating these effects results in the following composite map.

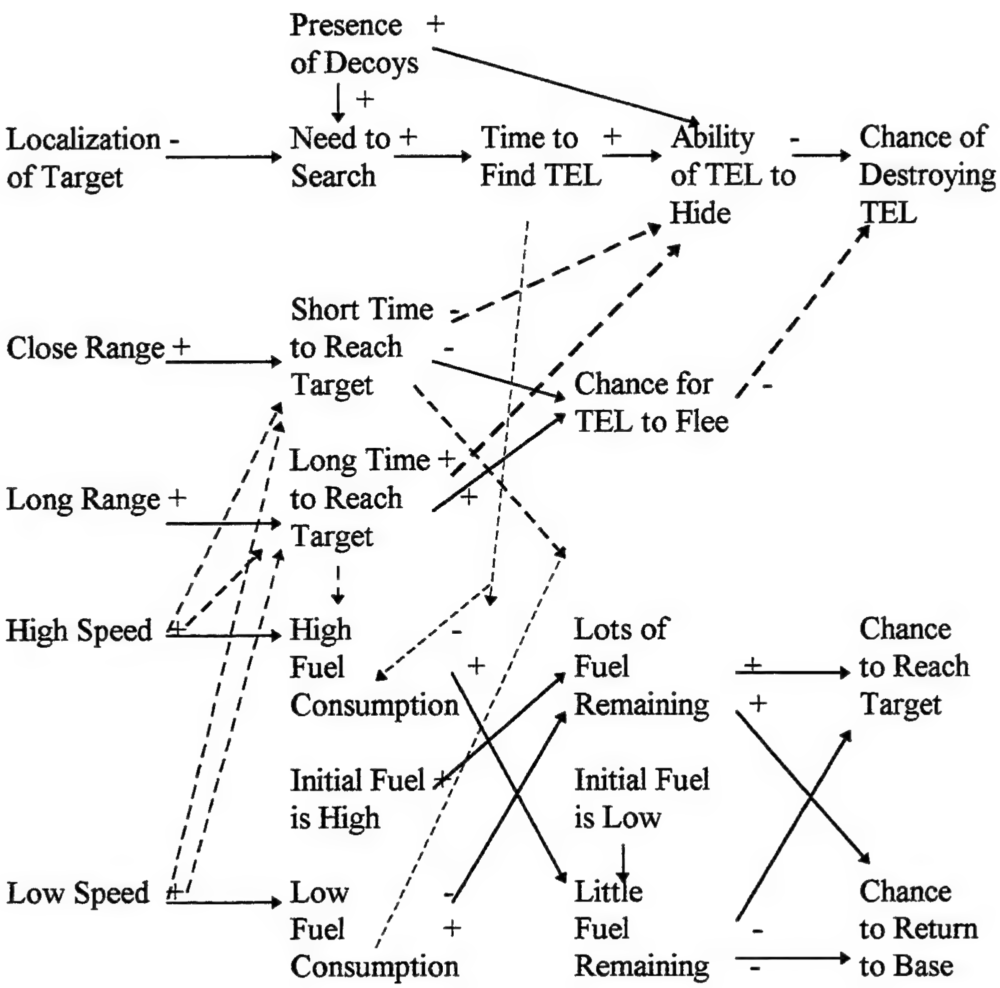


Figure 9. Combined Fuzzy Cognitive Map of Causes that Affect Destroying the TEL, Reaching the Target and Returning to Base

Attacking the Target and Surviving

A successful attack by an F-15 on a TEL will be impacted by several factors. A ground attack weapons load will increase the ability of an F-15 to attack a TEL. Anything that reduces the survivability of the F-15 will reduce the chances that the F-15 actually attacks the TEL. Enemy air defenses will increase the threat to the survivability of the F-15 as will a reduction in the favorability of the terrain to the F-15. Increasing the air defense weapons load of the F-15 will tend to negate the effects of the enemy defenses and increase the chances that the F-15 survives.

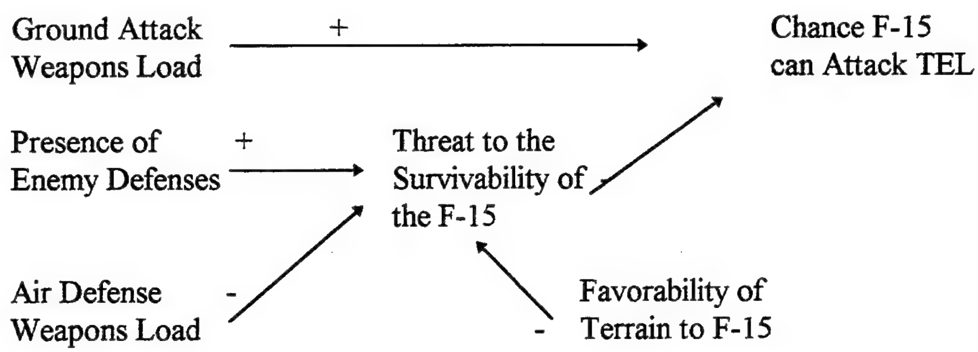
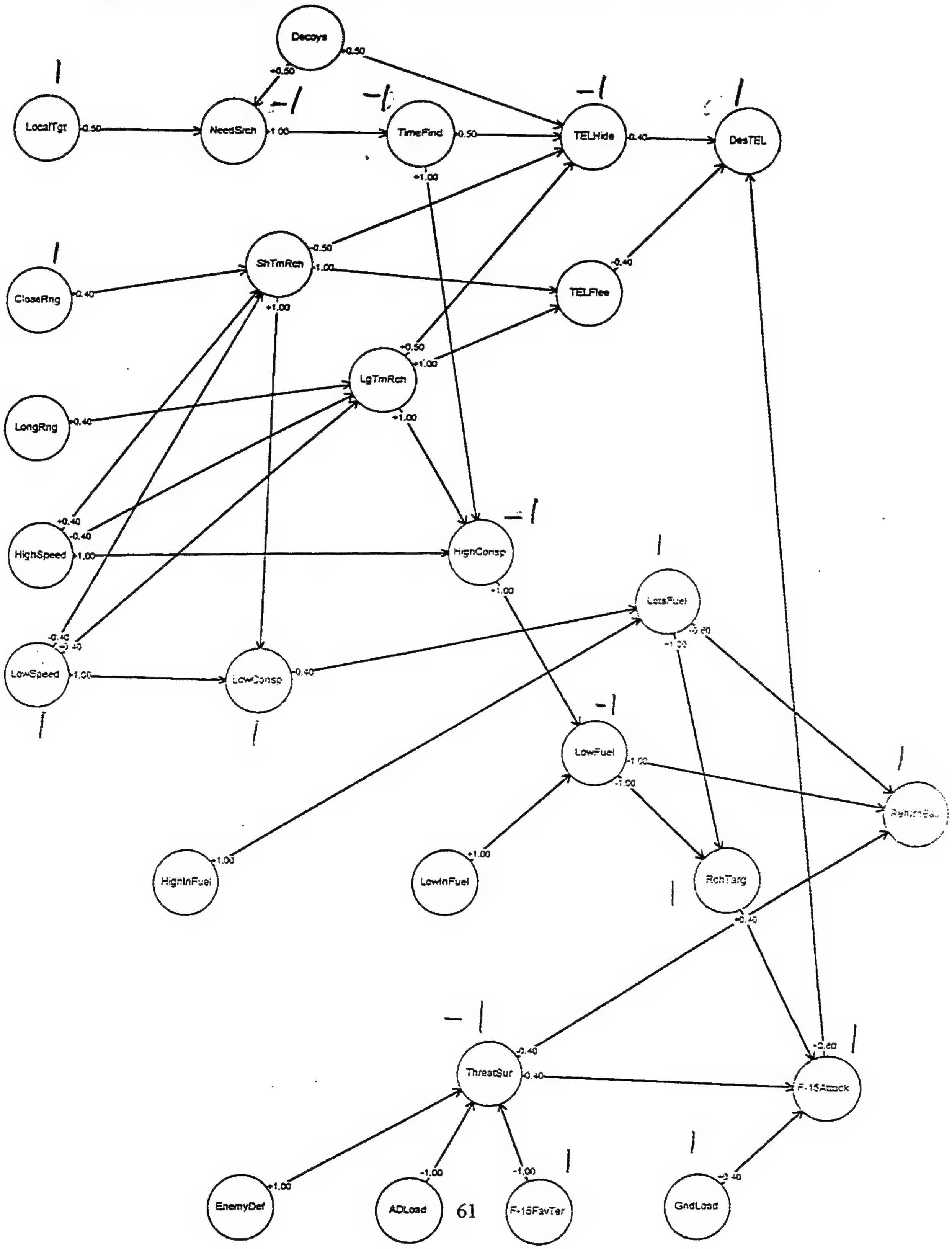


Figure 10. Cause/Effect Relationships on Attacking the Target and Surviving

In addition, increasing the threat to the survivability of the F-15 will reduce the chances that it will successfully return to base. Increasing the chances that the F-15 can reach the target will increase the chances that the F-15 can attack the TEL. The more likely that the F-15 can attack the TEL, the more likely it will be destroyed. A composite map is given in the following figure incorporating these changes and the previously constructed submaps.

Figure 11. Completed Fuzzy Cognitive Map for an F-15 Attack on a TEL



4.6 Assessing Edge Strength Values

In many instances of the map, a single node will be affected by several other nodes. To assess edge strength values for these cases, use will be made of the *causal independence* of a node. Causal independence means that each node is function of only the current state values of the nodes causing it, and independent of node states elsewhere in the map. Determining the edge strength values can then be determined from the combinations of causing nodes that give the effect. These combinations are then scaled against the threshold value used for mapping nodes to state values. For this map a threshold value of 0.5 is used.

Need to Search

The presence of decoys will increase the need to search (cause *Need to Search* node to be 1), while initial localization of the target will decrease the need to search. Also, these two effects will cancel each other if both are present at the same time. Edge strength values of 0.5 will be used. If either *Presence of Decoys* or *Localization of Target* is independently 1, then the *Need to Search* will be 1 or -1 respectively after thresholding. If both are 1 at the same time, then the *Need to Search* will be 0 after thresholding, giving the required behavior.

Ability of TEL to Hide

This node is affected by four other nodes: *Presence of Decoys, Time to Find TEL, Short Time to Reach the Target*, and *Long Time to Reach the Target*. Anyone of these will cause this node to change state (either 1 or -1), so an edge strength value of 0.5 is used.

Short Time to Reach Target

The nodes *Close Range, High Speed,* and *Low Speed,* all affect the node *Short Time to Reach Target*. To cause this node (change it value from 0 to 1) requires any two of the three causes be present at the same time, so any two edge strength values must add to a value greater than 0.5. An edge strength value of 0.4 will be used.

Long Time to Reach Target

Three nodes affect this node: *Long Range, High Speed,* and *Low Speed.* Like the previous node *Short Time to Reach Target*, any two of the three causes are need to cause this node, so edge strength values of 0.4 are used.

Chance for TEL to Flee

The node *Chance for TEL to Flee* is affected by two other nodes: *Short Time to Reach Target* and *Long Time to Reach Target.* Taking a long time to reach the target will tend to increase the chances that the TEL can flee, giving a positive edge strength value. Reaching the target in a short time would tend to decrease the chances the TEL can flee. Since it is anticipated that only one of the two time nodes will be active (state value=1) at any instance, the edge strength values are set to 1.

Lots of Fuel Remaining

This node is a function of the state values of two other nodes: *Low Fuel Consumption* and *High Initial Fuel.* Any fuel consumption will tend to reduce the fuel remaining. *High Fuel Consumption* will tend to cancel *Low Fuel Consumption* while *High Initial Fuel* will produce *Lots of Fuel Remaining* (=1). Given these state changes, the edge strength value from *Low Fuel Consumption* is -0.4, and from *Initial Fuel High* +1.

Little Fuel Remaining

The node little fuel remaining is determined by the state values for the nodes *High Fuel Consumption* and *Low Fuel Consumption.* Any fuel consumption will reduce the remaining fuel increasing the likelihood that little fuel will remain as will starting with little fuel. Thus, both edge strengths are given values of +1.

Chance to Reach Target and Chance to Return to Base

These nodes are caused by the remaining fuel nodes in symmetric ways: *Lots of Fuel Remaining* and *Little Fuel Remaining. Lots of Fuel Remaining* would increase the chances to reach the target or return to base, while *Little Fuel Remaining* would decrease the same chances. The edge

strength values from *Lots of Fuel Remaining* are set equal to +1, while the edge strength values from *Little Fuel Remaining* are set equal to -1.

Threat to Survivability of the F-15

This node is determined by the state values of *Presence of Enemy Defenses, Air Defense Weapons Load*, and the *Favorability of the Terrain to the F-15*. The presence of enemy air defenses would increase the threat to the survivability of the F-15, while the other two would tend to decrease the threat. The effect of enemy defenses would be negated by either an air defense weapons load or favorable terrain to the F-15. Thus, the edge strength values from *Air Defense Weapons Load* and *Favorable Terrain* are given values of -1, and the edge strength value from the *Presence of Enemy Air Defenses* is given a value of +1.

F-15 can Attack TEL

This node is effected by three other nodes: *Ground Attack Weapons Load, Threat to Survivability of F-15*, and *Chance to Reach Target*. To be able to attack the TEL, the F-15 must be able to reach the target and have a ground attack weapons load. Both must be present. If only one is present but not the other, the F-15 can not attack the TEL. Thus, the sum of the edge strength values for these two nodes must be greater than 0.5. A threat to the survivability of the F-15 will tend to offset either of the other two effects, so its edge strength value should be equal to either of the other two, but opposite in sign. A numerical value of 0.4 is used for the edge strength values of each with the signs described previously.

Chance to Destroy the TEL

The chances of destroying the TEL are affected by the ability of the TEL to hide or flee, and the ability of the F-15 to attack it. The TEL fleeing or hiding will offset the ability of the F-15 to attack the TEL, but the TEL can not be destroyed unless the F-15 can attack it. This implies that the sum of the values of *F-15 Attacks TEL* and either *TEL Hides* or *TEL Flees* must be less than 0.5, and the value of the *F-15 Attacks TEL* in the absence of the *TEL Hides* and *TEL Flees* must be greater than 0.5. So, in this case, the edge strength values from the TEL fleeing or hiding are

given values of -0.4, and the edge strength value from the ability of the F-15 to attack the TEL is given a value of +0.6.

4.7 Validating the Map

An important part of constructing a fuzzy cognitive map is applying known inputs to it and comparing the output values obtained against expected values. If the map does not give the desired results, then adjustments must be made in the edge strength values or connections. To validate this map five input combinations were used, listed in the following table along with the outputs produced by the fuzzy cognitive map. Note that in some cases, not all of the inputs had initial values. The inferred maps for these five scenarios are given in the figures at the end of the chapter.

	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
Localization	1	-1	1	1	-1
Decoys	0	0	1	0	1
Close Range	1		1		1
Long Range		1		1	
High Speed			1	1	
Low Speed	1	1			1
Initial Fuel High	1		1		1
Initial Fuel Low		1		1	
Gnd Attack Weapons	1		1	1	
Presence of Enemy Def.		1			
Air Defense Weapons		1			1
F-15 Favorable Terrain	1	-1	-1	-1	
Destroy TEL	1	-1	0	0	0
Return to Base	1	-1	-1	-1	0

Table 8. Results for Various Scenarios on Tasking an F-15 to Attack a TEL

Scenario A

In this scenario conditions are favorable for attacking the TEL. The target is localized and there are no decoys present. It is close and the F-15 starts the mission with lots of fuel. The terrain is favorable to the F-15 and it is carrying a ground attack weapons load. For this case, the chances of destroying the TEL and the F-15 returning to base both increase.

Scenario B

In this scenario the localization of the target is decreased and decoys are present. The range to the target is long. The F-15 uses high speed to reach it but starts with low initial fuel. The favorability of the terrain to the F-15 is reduced and enemy air defenses are present. The F-15 is carrying an air defense weapons load and not a ground attack weapons load. In this scenario the chances of destroying the TEL and the F-15 returning to base decrease.

Scenario C

The localization of the target is increased and TEL decoys are present. The range to the target is close and the F-15 uses high speed to reach it. The initial fuel is high. The F-15 has a ground attack weapons load and the terrain is unfavorable to the F-15. In this scenario the chance of the F-15 returning to base is decreased. The chances of destroying the TEL are unchanged. Since the initial equilibrium of the map assumes the TEL is intact, an *unchanged* condition in this node means the TEL is not destroyed.

Scenario D

The target is localized, but at long range. The F-15 uses high speed to reach it, but starts with low initial fuel. The aircraft has a ground attack weapons load and the terrain is favorable to it. For this scenario the chances the TEL is destroyed are unchanged and the chances the F-15 returns to base decrease. So, in this scenario, the TEL can be assumed to be intact after this mission.

Scenario E

The localization of the target decreases and decoys are present. The range is close. The F-15 starts with high initial fuel and low speed to reach the target and carries an air defense weapons

load. For this scenario, the chances of destroying the TEL and the chances that the F-15 returns to base remain unchanged. As in the previous two scenarios, the TEL is assumed to be intact after the mission. There is no a priori initial equilibrium states for the F-15 returning to base, so this result is ambiguous. It can be said neither that the F-15 will return to base nor that it will not return to base.

For this map there are 12 *inputs* (listed in the next table), and 2 outputs, *Destroying the TEL* and the *F-15 Returning to Base*. The 12 inputs can be broken in three categories, status of the F-15, target information, and information about enemy defenses. Of these aircraft speed (*High Speed and Low Speed*) and, to a lesser extent, the F-15 weapons load (*Air Defense Weapons Load and Ground Attack Weapons Load*) are the only nodes that are choices available to a decision maker. The other input nodes represent initial status information about the battlespace environment in which the mission is undertaken. These initial conditions are generally fixed.

Inputs:		
	Status of F-15:	High Fuel, Low Fuel, High Speed, Low Speed, Air Defense Weapons Load, Ground Attack Weapons Load
	Target Information:	Localization of Target, Close Range, Long Range F-15 Favorable Terrain
	Enemy Defenses Information:	Presence of Enemy Defenses, Presence of Decoys

Table 9. Input/Output Nodes for Tasking an F-15 to Attack a TEL

Of the five scenarios outlined above only A meets the criteria given previously for tasking the F-15 for the mission. It is the only scenario in which the F-15 will return to base and the TEL will be destroyed. In the other four scenarios, the F-15 is unlikely to return to base or the TEL is unlikely to be destroyed, or both.

Figure 12. Fuzzy Cognitive Map for Scenario A

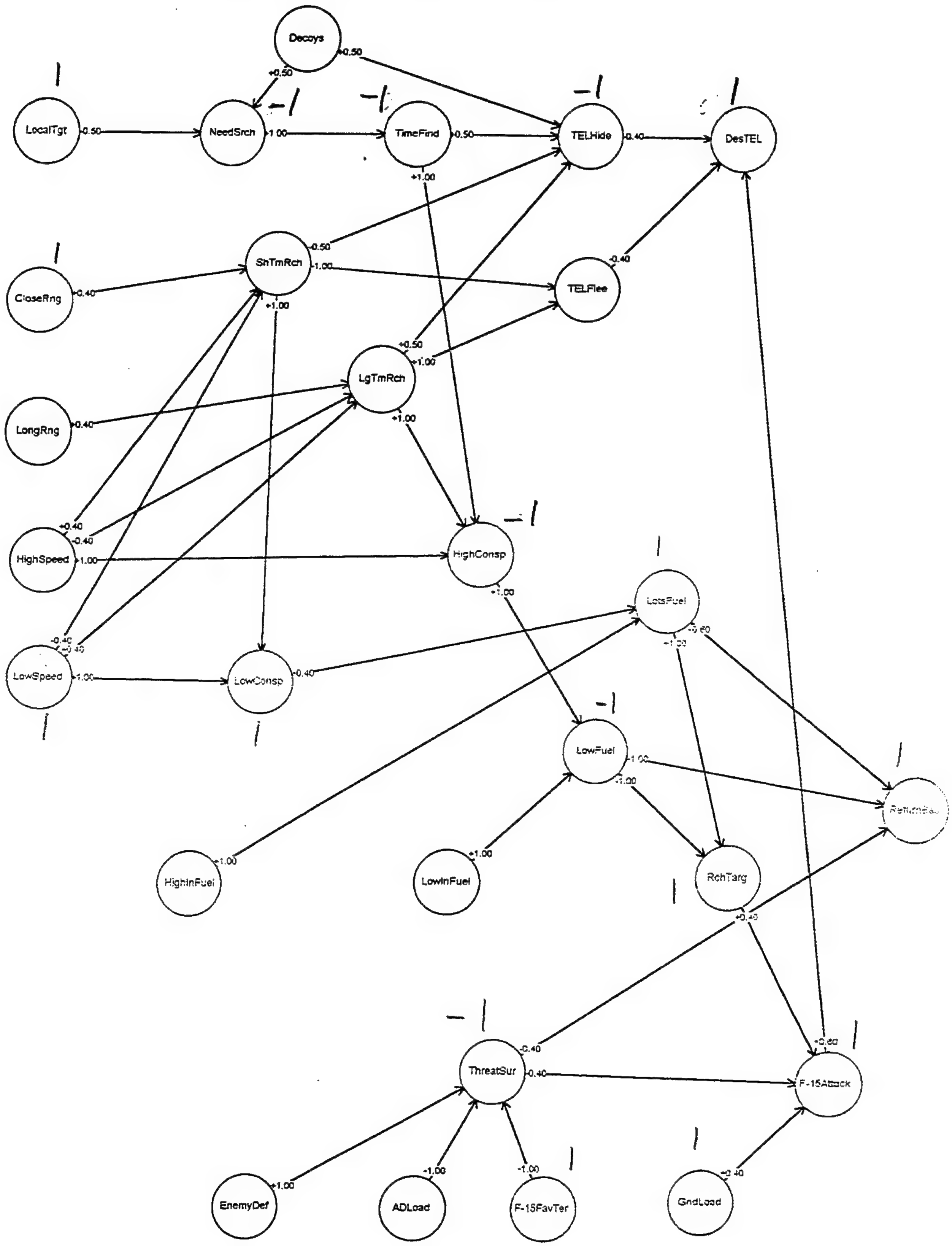


Figure 13. Fuzzy Cognitive Map for Scenario B

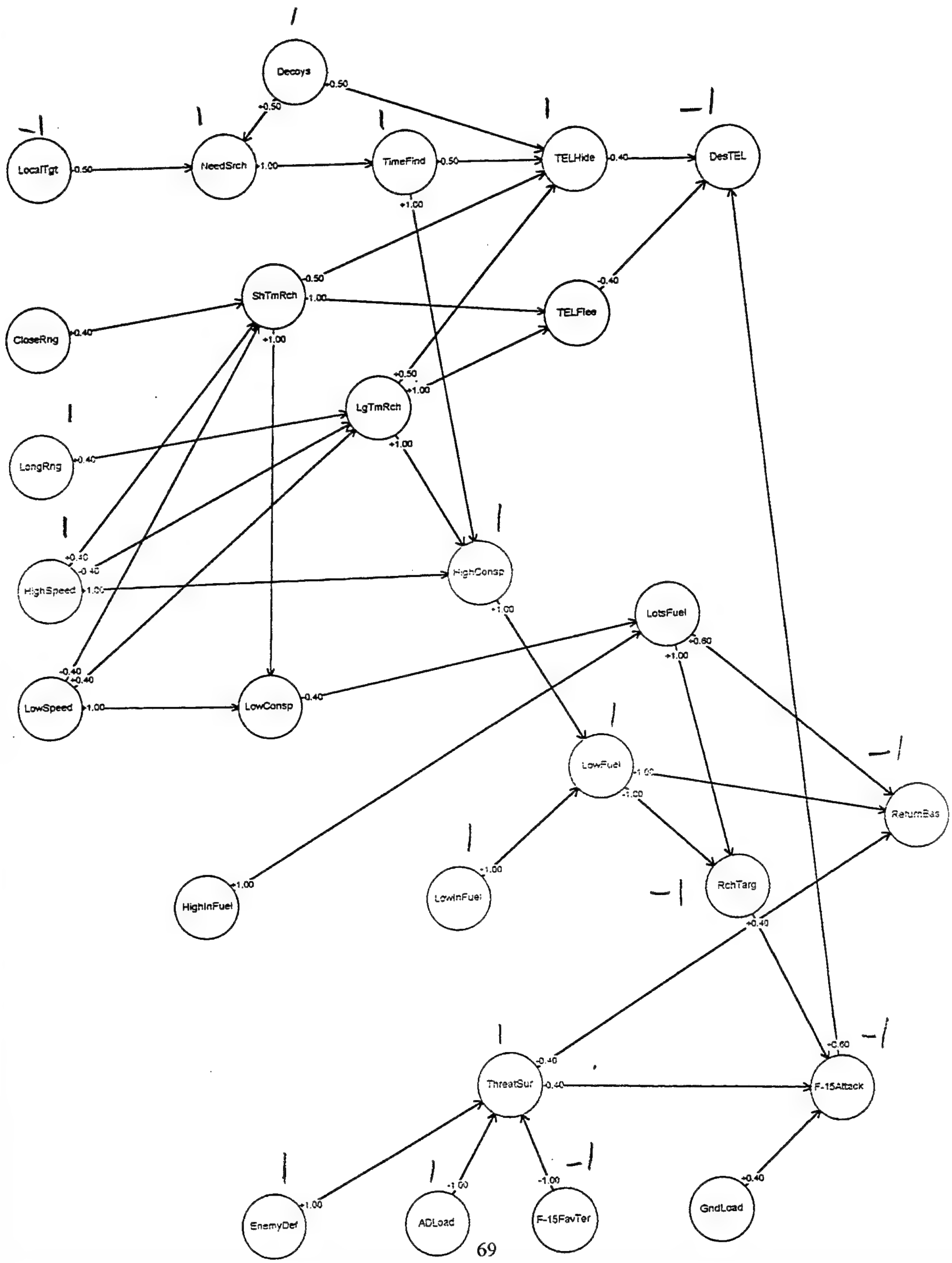


Figure 14. Fuzzy Cognitive Map for Scenario C

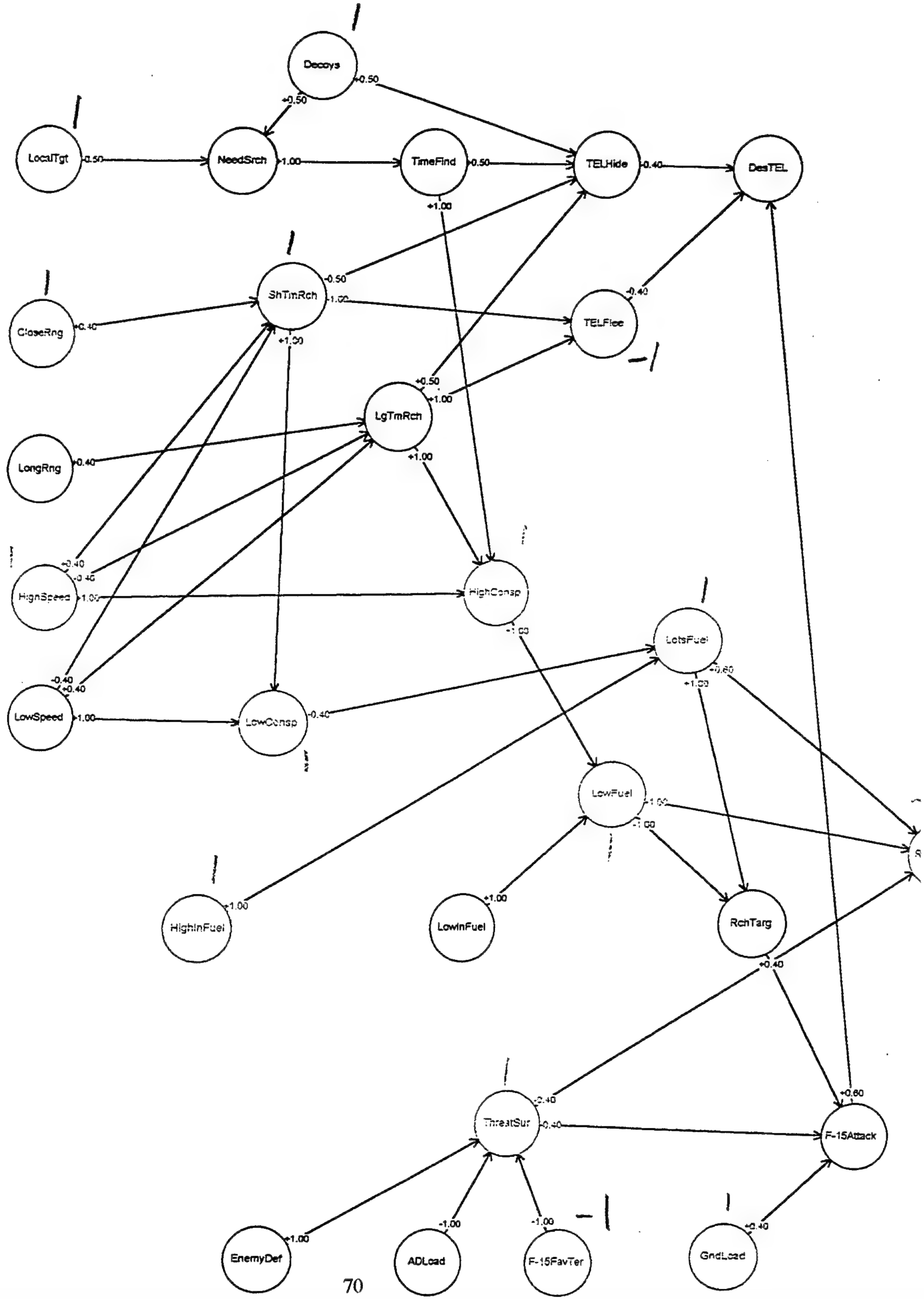


Figure 15. Fuzzy Cognitive Map for Scenario D

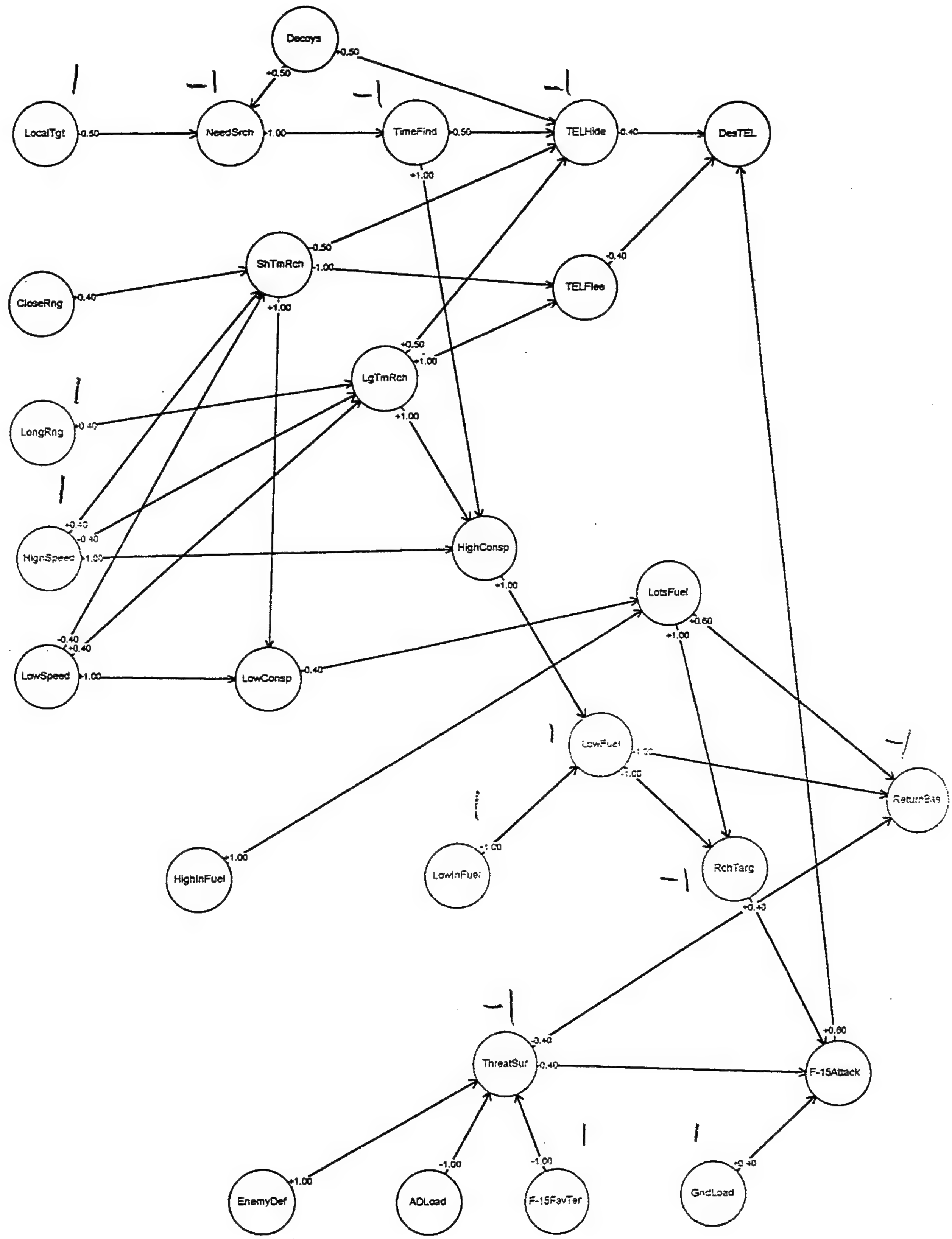
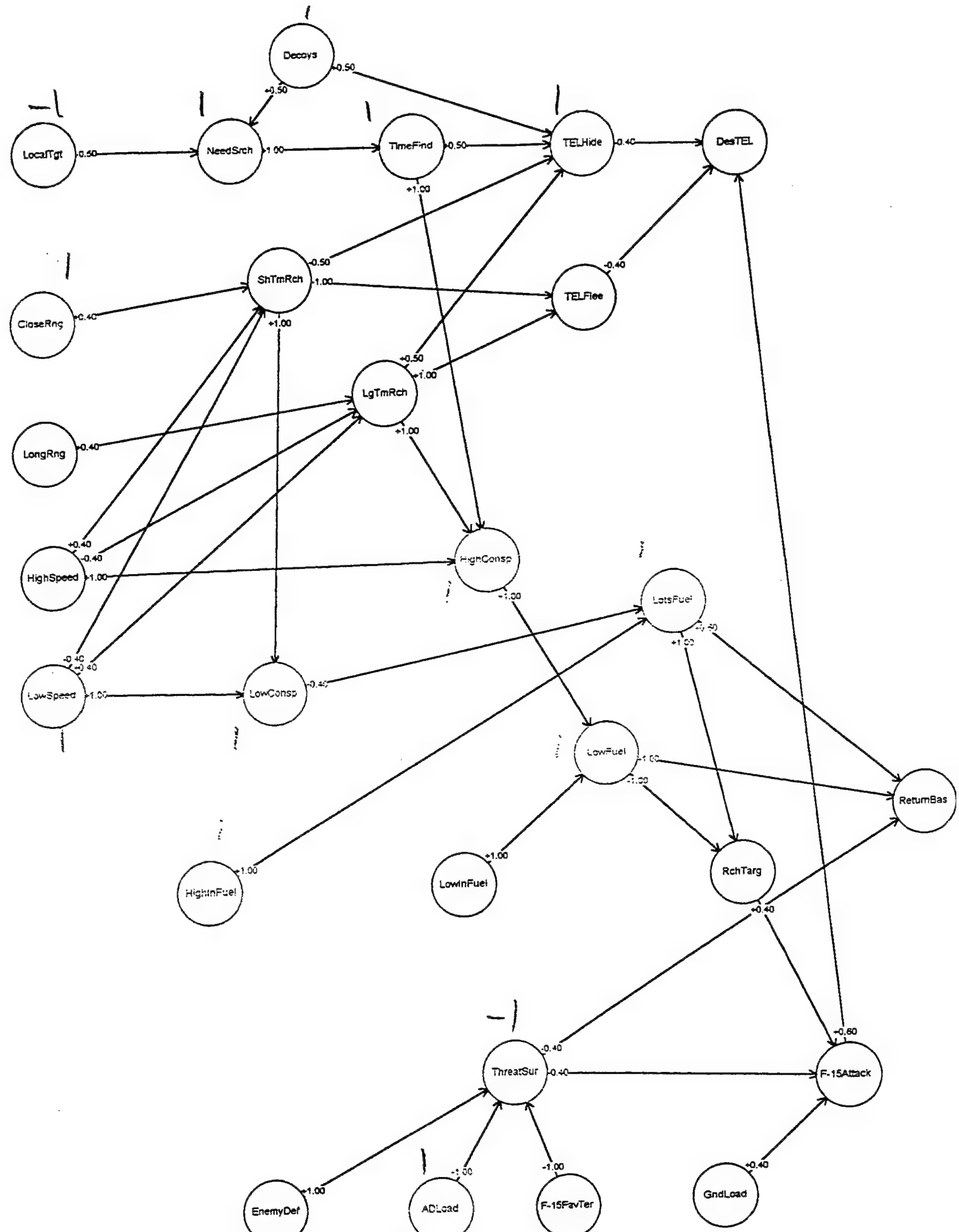


Figure 16. Fuzzy Cognitive Map for Scenario E



4.8 Dynamic Mission Management

To achieve the situational awareness required for information dominance, decision makers must be able to use available data and information to project future states or changes in states as the mission evolves. As new information becomes available or available information changes the perceived situation in which the mission is embedded may change, possibly requiring goals or actions of the units involved to change. These state changes may be obvious, in which case the operator will most likely properly identify the change and take the appropriate action. In other cases the state change may be more subtle and less obvious. If the operator is not focused on the proper data needed to recognize the change, it may be missed.(Endsley 1997)

If situated learning is defined as recognizing a change in one's perception, then an operator who is not focused on the right data may not learn to adapt to the changes that emerge from his or her environment. If more than on operator in a complex, interdependent collaborative system fails to keep the structured learning in pace with the environment and mission parameters, then shared situational awareness goes awry and perhaps may never be recovered as the mission progresses.

Fuzzy cognitive maps can be used to assist situated learning, as a meta-model of the battlespace. As new information becomes available the map can be updated, and changes in key output nodes assessed. These changes in outputs may then dictate new courses of actions. Used in this way, the fuzzy cognitive map represents a dynamic, qualitative model of the battlespace incorporating information about the status of the systems involved, the goals, actions and perceptions of the decision makers, the quality of information used, and, when available, similar types of information about the adversary. The fuzzy cognitive map gives the decision maker a tool for evaluating the potential results of courses of action that can be updated as the battlespace environment changes.

To illustrate this, consider the case from the previous section in which the F-15 is tasked to attack the TEL (scenario A). In this case, the target is localized and at close range. The F-15 will use low speed to reach it and starts with high fuel initially. The terrain is favorable to the F-15 and it is carrying a ground attack weapons load. No information is used in the map (i.e. node is 0) about

the enemy defenses (decoys, presence of enemy defenses). Under these circumstances, the map *predicts* that the TEL will be destroyed and the F-15 will return safely to base. The *state* of the environment is defined by the node values determined once the map has equilibrated for these inputs.

Assume that as the mission progresses information becomes available that enemy decoys are present in the target area. This information might come from visual sightings by the F-15 pilots or from other platforms in the area. Such information can now be used in the map to assess whether the *state* of the battlespace has changed and in what way. And even more specifically, this new information can be incorporated into the map to judge whether desired values for the output nodes change, indicating a change in mission results.

Using the equilibrium values established from propagating the inputs from scenario A through the map, a baseline state is established for the mission. Using these values, the new information about decoys is incorporated in the map by changing its node from 0 to 1 indicating their presence. The map is again allowed to equilibrate and the new *state* of the battlespace established. In this new case, the outputs partially change. Returning to base is still predicted, but destroying the TEL is not.[1]

Additionally, the map provides a graphical way to trace the chain of causality (i.e. decision rationality) that has led to the change. In the first map, from which the F-15 was tasked, the increased localization of the target led to a decrease in the need to search for the TEL leading to a decrease in the time to find it. Decreasing the time to find the TEL reduced the ability of the TEL to hide. This, coupled with the ability of the F-15 to attack the TEL, led to the increase in the likeliness of its destruction.[2]

In the new map, incorporating the presence of decoys[3] this chain of causality is altered. Although the target is localized, decreasing the need to search for the target, the presence of decoys

[1] The node value for *Destroy TEL* changes from 1 in the previous map to 0 in the new map.
[2] The destruction of the TEL is indicated by a value of 1 for the node *Destroy TEL*.
[3] The presence of decoys is incorporated by setting the node *Decoys* equal to 1.

produces the opposite effect. It increases the need to search for the TEL. These two effects cancel, producing no change in the need to search for the TEL.[4] Since the need to search is unchanged, the time to search for the TEL is unchanged.[5] Since the time to find the TEL is unchanged, it has no effect on the ability of the TEL to hide. The presence of the decoys, though, will increase the ability of the TEL to hide.[6] The increase in the ability of the TEL to hide offsets the ability of the F-15 to attack the TEL, so the chances of destroying the TEL are unchanged. As described previously, it is assumed that the initial state for this node is that the TEL is intact, so a value for this node of 0 can be interpreted as the TEL avoiding destruction. Thus, the presence of decoys produces a fundamental change in the mission results, and aborting it would be the correct course of action.

4.9 Data Abstraction

This example also illustrates an important point about data abstraction. To achieve information dominance, data and information must be perceived properly by all decision makers involved in the battlespace to effect situation awareness. (Endsley 1997) Even in the *simplified* map presented here for tasking an F-15, the inter-dependence of the factors affecting the battlespace environment can become confusing. Hidden relationships exist between concepts. If the decision maker does not perceive the different relationships or focuses on only a few relevant factors to the goal at hand, possibly because of time stresses, then key information can be missed or ignored. This occurs especially when the key information is most relevant to subgoals not currently under consideration by the decision maker. Such miscues reduce the correct perception of the situation by the decision maker, handicapping their ability to deal with the dynamically changing environment.

Reducing the *raw* information the decision maker must deal with through data abstraction can partially alleviate this problem. By combining data such as system status with goals and constraints, there is less information for the decision maker to assimilate. Further, if the data is abstracted in a consistent way, then the decision maker can be presented with the status of the

[4] This is indicated by a nodal value of 0 for *Need to Search*.
[5] *Time to Find* equals 0.
[6] This is indicated by a nodal value of 1 for *TEL Hide*.

environment rather than being required to use individual data and construct the status themselves. Constructing the status will require time that may not be available, and key relationships between concepts may be ignored to simplify the process.

Fuzzy cognitive maps represent a dynamic qualitative model of the environment in which the decisions are embedded. As such, it can be used as a tool for data abstraction. [12] By judicious choice of nodes to be given decision makers, the data presented can be reduced, but the underlying dynamics and context can be preserved. The map acts as a mediator between the input information (i.e. input nodes) and the outputs (i.e. output nodes), synthesizing inputs through the complex web of relationships that define the solution space into outputs. The map can be used to preserve all of the relationships that exist in the battlespace, allowing the decision maker to focus on those abstract concepts most relevant to achieving situational awareness. If the map has been properly validated and the relationships defined in its topology are accepted, then much of the information (i.e. node values) contained in the map can remain safely hidden.

For the previous maps, the tasking of the F-15 was made on the basis of only two nodes, whether the F-15 will return to base, and whether the TEL is destroyed. The information contained in the map could be *abstracted* by giving the decision maker only the values of these two nodes. Although the values of the other nodes, such as fuel consumption and threat to the survivability of the F-15, are relevant to constructing the battlespace, knowing their values is not critical to making the decision of whether to task the F-15 or not. The complexity of reasoning involved in even this *simplified* map was demonstrated in the previous section. By using the map as a model to *synthesize* much of the data into more abstract forms, the volume of information is reduced and the decision maker is more likely to achieve a better perception of the situation they are in.

As was stated previously, display format (both spatial and temporal) can play a key role in developing or hindering the development of situational awareness. In the Battle of Britain, situation maps and tote boards were used by commanders to develop situational awareness of the evolving battle. These situated displays provided the correct data with a minimum of extraneous information for a commander to develop a global understanding of the battlespace. This

assessment of the situation was then communicated to subordinate units. The situational assessment made was then common across units because it was imposed from a central command authority.

In a modern battlefield, such a central command authority would probably not be able to develop an accurate assessment of the situation in the time necessary before a task must be undertaken. Different actors within the battlespace will have to develop a correct (and common) assessment independently using shared data. By utilizing a fuzzy cognitive map, such a common assessment becomes more likely. Additionally, the fuzzy cognitive map provides a way to synthesize the data reducing the interpretative overhead necessary during inter-unit communication. The map provides a way for identifying only what information each unit needs for making an assessment. Using the previous example, a surveillance asset might need to know only whether an F-15 can successfully attack the TEL and whether it can return to base to *understand* the current conditions of the battlespace and take its actions accordingly. If this is the case, then the F-15's need only to communicate that they can attack the TEL and that they will return to base the surveillance asset. The other nodes could safely remain hidden from the surveillance asset. This has the added advantage the commander of the surveillance asset will focus on only those nodes of relevancy and not on extraneous nodal information because it would not be available.

4.10 Incorporating Numerical Information

For this example, none of the edge strength values readily lends themselves to modeling using a technique that incorporate values derived from a physical process. Numerical information can be used, though, to place bounds on the speed the F-15 uses to reach the target once it is tasked. Of the several inputs incorporated in the map, three sets deal with the *flying* status of the F-15: the initial fuel available, the range to the target, and the speed of the aircraft in reaching the target. Of these, the initial fuel and range to the target are set when the mission is evaluated, while the speed of the F-15 is a *variable* in the sense that its value is chosen.

The map can be used to place bounds on the velocities of the aircraft that can be chosen and still meet the tasking criteria, as derived from the map. The basic process is to couple the required

states of the input variables, in this case initial fuel and range to target, with membership functions that define their fuzzy values. The idea is to find minimum or maximum values of the inputs that have the proper membership values to give the state values required by the map for the particular inference. As described previously, the F-15 should only be tasked to attack the TEL if the range is close, the speed used is low, and the initial fuel is high. To identify numerical values for range, speed, and initial fuel, fuzzy membership functions must be constructed for such states as *High Initial Fuel* from which the required range can be extracted.

High Initial Fuel

A series of assumptions will be used to construct these fuzzy membership functions.[7] The membership values for this variable will be a function of the range to the target and the velocity used, so in some sense *High Initial Fuel* is defined relative to the situation and is not absolute. For example, for the same amount of initial fuel, the closer the F-15 is to the target initially, the more fuel will be left after the mission, the stronger the case that the initial fuel was *high*. Intuitively, classifying the initial fuel as high or low makes most sense in relation to how much is left once the mission is completed. Given this the following, somewhat arbitrary, heuristic will be used:

$\mu = 0$ if $Fu > Fi$

$\mu = 1$ if $Fi - Fu > 0.2\ Fi$

where μ = the membership value that the initial fuel is *high*

Fi = the initial fuel

Fu = the fuel used

The first criteria simply says that if the fuel used on the mission exceeds the initial fuel, then the membership value is 0, i.e. the initial fuel was definitely not *high* to begin with. The second criteria assumes that in tasking an asset a *margin of safety* should exist for fuel limits for the best

[7] This example is intended only to illustrate the methodology being used, and is not intended to reflect any real world problem or mission.

cases. This criteria says that the remaining fuel (Fi-Fu) after the mission should be at least 20% of the initial fuel. Membership values between these two limits will vary linearly.

The fuel used during the mission, Fu, has two components, the fuel used to reach and attack the target, and the fuel used to return to base. To simplify the analysis, it will be assumed that the fuel used to return to base is always 20% of the initial fuel. Given the range to the base from the target, the velocity will always be adjusted so that the fuel used is 20% of the initial fuel. So, defining Fu' as the fuel used to reach the target, the fuel used in the mission is:

$$Fu = Fu' + 0.2\ Fi$$

Using this definition, the heuristic becomes:

$\mu = 0$ if $Fi < 1.25\ Fu'$

$\mu = 1$ if $Fi > 1\ 2/3\ Fu'$

The following is a graph of the membership function.

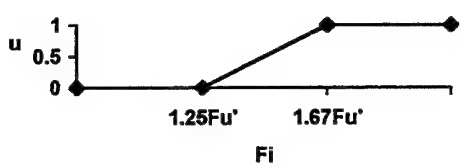


Figure 17. Membership Function for Initial Fuel

To task the F-15 the state *high initial fuel* must be a 1, so the membership function is used to identify those values of Fi which give this required state value. Using the same thresholding idea used in inferring state values in the fuzzy cognitive map, a value of $\mu>0.5$ will give a state value of 1. Examining the graph for the membership function of *high initial fuel*, it can be seen that $\mu=0.5$ falls half way between the extremum of 1.25 Fu' and 1.67 Fu'. Thus, values of $Fi>1.4583$ Fu' will meet the requirement of $\mu>0.5$.

The fuel used will be a function of both the velocity taken and the range to the target. The fuel used will be assumed to be of the form $Fu' = \alpha V_T R_T$. For a given range to the target, increasing the velocity will increase the fuel used. α is a constant of proportionality. Likewise, for a given velocity, increasing the range to the target will increase the fuel used. Using this definition of the fuel used in reaching the target, the condition defined previously can be rewritten as:

$$Fi > 1.4583\ \alpha V_T R_T$$

This gives one of two conditions on the velocity range given the initial fuel and the range to the target to meet the state conditions required for the fuzzy cognitive map.

Range to Target

The second parameter that will be given at the time that the F-15 is tasked is the range to the target. Tasking the F-15 requires that the range to the target be in the state *close*. To identify the boundaries that this places on the velocity a membership function for *close range to target* will be constructed. The range to target will affect the time to reach it, in turn affecting whether the TEL can successfully flee. It will be assumed that if it takes more than 7 minutes to reach the target, the TEL has enough time to successfully flee and the chances of locating it are practically nil. It will also be assumed, arbitrarily, that reaching the target in under 4 minutes will reduce the chances that the TEL can flee to a minimum. Thus, the range to target will be considered definitely not close for times to reach the target that are greater than 7 minutes, and definitely close for times to reach the target less than 4 minutes. Using the transformation that the time to reach the target is the R_T/V_T, the membership function for *close range* becomes:

$$\mu = 0 \quad \text{if} \qquad R_T/V_T > 7$$

$$\mu = 1 \quad \text{if} \qquad R_T/V_T < 4$$

The membership grade for values in between these limits is assumed to vary linearly. This membership function is displayed in the following figure:

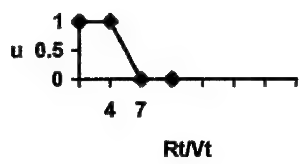


Figure 18. Membership Function for R_T/V_T

Again, to meet the requirement that the state value for the range to the target be *close*, the values for which $\mu > 0.5$ will be identified. The mid-point between 4 and 7, from the graph is 5.5, so the following condition must be met for the *close range* to be 1:

$$R_T/V_T < 5.5$$

This, with the condition derived from for the initial fuel, will define a range of permissible values for the velocity, given the initial fuel and the range to the target.

Given that fuzzy membership functions are constructed external to the fuzzy cognitive map for tasking the F-15's on SCUD-hunting missions, one can question whether the fuzzy cognitive map itself has any value in the decision process or whether it simply represents needless *clutter*. It must be remembered that the velocity conditions were derived from membership functions for the range to the target and the initial fuel available, *and* knowledge of the states, derived from the fuzzy cognitive map, for which conditions are favorable for tasking the F-15. The state values in turn are derivatives of the equilibrium conditions of the map that represent the conditions of the battlespace for which the F-15 can be tasked. This battlespace condition includes information about the status of the aircraft, the goals of the mission, and the intentions of the adversary. Thus, by using the fuzzy cognitive map, a variety of information is used in the decision making process that probably would not be.

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A. Inference in a Fuzzy Cognitive Map using Hybrid Number Edge Strengths

A.1 Introduction

A hybrid number is characterized by the pair a_i and f_i, where a_i represents a fuzzy number and f_i represents a probability distribution. In general, a_i and f_i are defined on R, but in fuzzy cognitive maps their definition is restricted to the interval [-1,1]. The hybrid number A_i is defined as:

$$A_i = (a_i , f_i)$$

Some basic properties of hybrid numbers are:[1]

Addition

$A_1+A_2=(a_1(+)a_2,f_1(+)'f_2)$

where (+) is any appropriate addition operator for fuzzy numbers

(+)' is sum/product convolution for probability distributions

Image (Subtraction)

Given $A_1=(a_1,f_1)$, its image, written as $-A_1=(-a_1,-f_1)$ is defined as:

$-a_1$: $\mu_{-a1}(-x)=\mu_{a1}(x)$

$-f_1$: $g(-x)=f(x)$

The image of a hybrid is its reflection through the Y axis. Subtraction of hybrid numbers is accomplished by adding the images of the negative hybrid numbers.

Expectation of a Hybrid Number

[1] See pages 79-117, (Kaufmann 1991)

The expectation of a hybrid number is defined as:

$$\xi(A)=a+\xi(f)$$

where $\xi(A)$ is the expected value of the hybrid number

a is the fuzzy number component of A

$\xi(f)$ is the expected value of the distribution f

f is the stochastic component of A

The expected value of the hybrid number A is a fuzzy number. It is the fuzzy number component of A shifted by the expected value of the stochastic component f.

A.2 Adding Hybrid Numbers in an FCM Map Fragment

The following figure shows a typical map fragment from a fuzzy cognitive map. In the submap, the effect C is caused by two nodes A and B. The strength of the causal connection between A and C is defined as e_{AC} and is a hybrid number. Likewise the edge strength from B to C is defined as e_{BC} and is also a hybrid number.

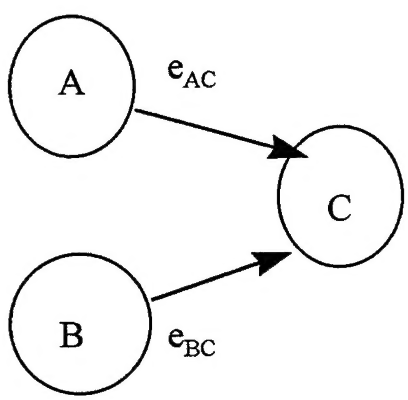

Figure 19. Fuzzy Cognitive Map Example

The value of C is determined from:

$$C = \mathbf{T}[\, A^* \, e_{AC} + B^* \, e_{BC}\,]$$

In this operation A, B and C are restricted to values of -1, 0 and 1. **T[]** is a thresholding operation that maps the result of the summation to -1, 0 and 1. Updating the value of C involves two steps. First, sum the causing states weighted by their edge strengths. Second, threshold the result using some appropriate operator to define C as either -1, 0 or 1.

A.3 Summing Causing Nodes

Connections with a causing node equal to 0 are ignored. The 0 value means the cause is not present, which is the same as saying that the connection is not present. Causing nodes with values of 1 are weighted by their edge connections and summed directly. Since causing nodes with values of -1 subtract from the overall effect, the image of the edge strength is used in these cases in the sum.

In the general case, let X_j be the effect node, X_i be a causing node, e_{ij} be the edge strength from causal node i to effect node j, and $-e_{ij}$ its image. The value of the effect node before thresholding can be determined from:

$$X_j = \Sigma_{Xi=1}\,(e_{ij}) + \Sigma_{Xi=-1}\,(-e_{ij})$$

The value of the effect node before thresholding is the result of summing the edge strengths of all the causal nodes with values of 1 and summing the images of the edge strengths of all the causal nodes with values of -1.

To threshold this result and map its value to one of the state values of 1, 0 and -1, the expected value is needed. The expected value of X_j is:

$$\xi(Xj)= \Sigma_{Xi=1}\, a_{ij} + \Sigma_{Xi=-1} -a_{ij} + \Sigma_{Xi=1}\, \xi(f_{ij}) + \Sigma_{Xi=-1}\, \xi(-f_{ij})$$

where quantities in this equation have the definitions given previously. The expected value of the effect node before thresholding, which is a fuzzy number, is the sum of the fuzzy number components of the causal nodes shifted by the sum of the expected values of the stochastic components of these nodes. When the causing node is -1, the images of these components are used in the summation.

A.4 Thresholding

Once a value is computed for the effect node, some operator is used to map the value to one of the valid state values of -1, 0 or 1. When working with hybrid numbers several such operators are possible: fuzzy optimum and arbitrary order relations to name two.[2] For purposes of mapping state values in a fuzzy cognitive map, using the distance of the expected value of the hybrid number to prototypes for the fuzzy numbers *about -1*, *about 0*, and *about 1* will be used as the thresholding operation. The state value of the prototype *closest* to the hybrid as measured by its fuzzy distance is the state value used for the node.

The expected value of the hybrid number for the effect node has been defined previously. It must be remembered that this result is not a single numerical value, as would be the case with a stochastic variable, but is a fuzzy number. The distance between the fuzzy number representing the expected value of the effect and the prototype for one of the state values can be calculated from:

$$d = \int |X_1 - P_1| \, d\alpha + \int |X_2 - P_2| \, d\alpha$$

where X_1 is the left value of the effect node at membership level α

X_2 is the right value of the effect node at membership level α

P_1 is the left value of the state value prototype at membership level α

P_2 is the right value of the state value prototype at membership level α

[2] See pages 110-113 (Kaufmann 1991)

The integration is over the interval [0,1]. The distance, d, is a number that incorporates differences between the prototype and the effect node result at all levels of membership from 0 to 1. The effect node is set equal to the state value definition for the prototype with the smallest value of d, i.e. is the closest to the prototype in shape.

Using this distance measure has two desirable properties. If the result for the effect exactly matches a prototype, then the distance measure, d, will be 0. Also, if the edge strengths are defined as crisp fractional values on the interval [-1,1] then using this operator is the same as using a greater than or less than operator for the thresholding operation.

Although a variety of shapes can be used to define the fuzzy numbers for -1, 0 and 1, the following triangular shapes are generally effective and relatively simple to work with.

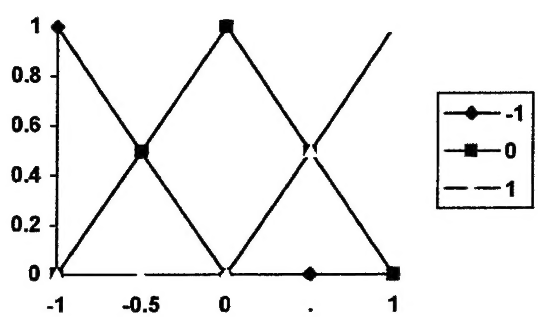

Figure 20. Template Membership Functions for Fuzzy Numbers -1, 0, 1